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STRUCTURAL MATERIALS W.F. Brown, Jr.
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REPORT OF THE NASA AD HOC COMMITTEE ON FAILURE
OF HIGH STRENGTH STRUCTURAL MATERIALS

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REPORT OF THE NASA AD HOC COMMITTEE ON FAILURE OF HIGH STRENGTH STRUCTURAL MATERIALS

ABSTRACT

The Charter of the Committee as established by the Deputy Administrator was twofold; namely, to collect and publish information on NASA's structural failures that have occurred during the past few years, and to determine what additional research NASA should perform to reduce the risk of future failures.

In carrying out this assignment the Committee reviewed the reports of 231 examples of structural failures encountered over the last 5 years in NASA's programs. Attempts were made to identify those factors which contributed to the failures, and recommendations were formulated for actions which would minimize their effects on NASA's future programs.

The factors identified fall into two general classes:

- (1) Those associated with deficiencies in the existing materials and structures technology
- (2) Those attributable to inadequate documentation or communication of that technology

The Report summarizes the conclusions and recommendations of the Committee. Detailed discussion and supporting information are presented in the Appendices.

The Committee found that during the past 5 years NASA has been relatively free of in-flight failures that could be attributed to deficiencies in materials or structures. Most of the failures involved ground equipment, development hardware, or the ground testing of flight hardware. A major conclusion of the Committee is that very few structural failures could be attributed to deficiencies in the technology of high strength materials and structural analysis. However, these few were very serious and had a large impact on both program cost and schedule. The great majority of failures were traceable to inadequate dissemination or utilization of available information, and to the unrealistic assessments of technology, cost, and schedule that too often characterize the initial planning stages of aerospace programs. It is important to recognize that NASA's future programs are more demanding in terms of high strength materials technology than any of its past projects. For this reason it is of vital importance to ensure adequate support for the R&D programs that provide this advanced technology.

The recommendations of the Committee are intended to provide NASA with procedures which should contribute significantly to a reduction in the risk of failure of aerospace structures. These recommendations can be placed in two classes:

- (1) Those which can be implemented through our present activities
- (2) Those that require additional procedures or new functions

A brief summary of these follows:

Class 1.

- A. While our materials and structures research programs are well balanced and have made substantial contributions to all pertinent areas of the technology, certain areas require intensification of effort. Included in these would be the study of fracture as influenced by crack like flaws (fracture mechanics), the influence of service environmental factors on fracture behavior, and the development of materials evaluation and design procedures for composite structures (see Section II).
- B. NASA should encourage DOD to continue funding of its technical information services, and NASA support should be increased for selected activities in this group. These services have been of considerable benefit to NASA over the past decade, but NASA contributes very little to their support. The total funding supplied to these services has been gradually reduced until at present it is about two-thirds of the 1969 level, and there is no assurance it will be continued after fiscal 1972. Further reductions would seriously reduce the effectiveness of these services, and their elimination would have an adverse effect on the efforts of both NASA and DOD to increase the integrity of aerospace structures (see Section III).
- C. The computerized literature searching facilities used by both NASA and DOD should be enabled to search for information on materials properties by identification through the common names of the materials. The present coding system does not permit this, and the facilities are therefore of only marginal value to the designer and materials engineer (see Section II).

Class 2.

- A. NASA's control over the use of high strength materials in critical structures should be substantially strengthened. This can be accomplished by requiring increased participation of materials application and structural analysis specialists in all phases of program planning and development. Specialists of these types at NASA Centers should be identified to the various program offices and under appropriate circumstances could be selected to serve on a Materials Review Board (see Section III).

NASA should formulate a set of Materials Guidelines which would identify particularly sensitive materials. Contractors using these materials should be required to show how this sensitivity is to be overcome.

- B. NASA should strengthen its internal mechanisms for collection, documentation, and dissemination of technical information in the following areas:
 - 1. Reporting and analysis of failures—an area where we are particularly weak
 - 2. Structural design and materials selection criteria—an area where present efforts should be expanded

3. Techniques and limitations of nondestructive evaluation (NDE) for both metallic and nonmetallic structures—a critical area requiring prompt attention to develop a useful function

It is recommended that a central office be designated within the OART which would have the responsibility of developing means for improving NASA's function in the above areas and working with the program offices to provide education to contractors in special cases where the technology is not well or widely known (see Section III).

INTRODUCTION

The Committee on Failure of High Strength Materials was established on June 22, 1970, by the Acting Administrator for Advanced Research and Technology in response to a request from the Deputy Administrator in a memorandum dated April 28, 1970 (see Appendix D). The purpose of the Committee was to identify and examine those factors which have contributed to structural failures of aerospace hardware as encountered by both NASA and the Air Force. The Committee directed its attention to three areas, namely (1) a review and analysis of selected reports for representative types of failures; (2) assessment of the technology that is available for material selection, and design of highly stressed aerospace structures; and (3) communication of information relating to this technology.

Panels of specialists selected from NASA Headquarters and NASA Centers studied each of these areas. This report represents a consensus of the Committee based on these studies. The individual Panel Reports are presented in Appendices A to D and represent the opinions of the authors based on their experience and interpretation of published information.

The Committee established liaison with a similar, but substantially wider ranging, Air Force investigation of recent experience with failure of aircraft structural materials. Two members of the Air Force Technology Subcommittee, R. F. Hoener of the Wright-Patterson Flight Dynamics Laboratory and J. J. Mattice of the Wright-Patterson Materials Laboratory, participated in the initial meeting and provided information on the organization of the Air Force activity. It was further agreed that the findings of the two studies would be exchanged.

Throughout this report special attention has been given to high strength materials, and it is useful to review briefly the reasons for this emphasis. Aerospace applications are particularly weight critical, and this inevitably leads to the use of materials having high ratios of strength to density. The Deputy Administrator in his request for this study pointed out that serious problems can be associated with the use of high strength materials in critical components. It is generally true that as the conventional tensile strength of a material is increased it becomes less "forgiving" in the sense that it is more sensitive to those factors which can severely limit its strength potential such as the presence of small flaws, corrosive environments, errors in fabrication, etc. Perhaps the most important, although simple, concept to evolve in the last decade is the recognition:

- (1) That we must accept the existence of cracks or crack-like flaws in our hardware, as produced, or that cracks will develop in service from such mechanisms as fatigue, or stress corrosion
- (2) That these cracks at some critical size may suddenly propagate to produce a catastrophic failure of a "brittle" nature
- (3) That the stress level at which this failure occurs can be well below the conventional tensile yield strength of the material

The crack size which can trigger a brittle failure depends on the material, its metallurgical condition, and the hardware geometry. Without exception, the tendency to brittle fracture increases with the thickness of the section containing the flaw. There

have been examples of flaws in thick walled pressure vessels which removed only 0.01 percent of the load-carrying area but reduced the expected load-carrying capacity by 50 percent.

From the foregoing discussion, it is obvious that high conventional safety factors may actually be dangerous, if they are achieved by increasing the strength level of the material, unless all phases of production are attended by a careful fracture control program which should include the best nondestructive evaluation methods as well as properly designed proof tests when these are appropriate. These steps require increased sophistication and more attentiveness on the part of the designers, fabricators, and inspectors. However, it is the nature of NASA's mission to require the application of high strength materials, and our materials and structures programs will emphasize overcoming their deficiencies and understanding their safe use.

SECTION I: REVIEW OF FAILURE REPORTS

This section summarizes the Committee's conclusions and recommendations based on examination of the structural failure experience of NASA during the past 5 years. The object of the study was to determine the availability of failure information and attempt to establish and classify the causes and mechanisms of failure. It was judged that such information would be useful in defining the types of research or other activities that would be helpful in reducing the risk of future failures.

Procurement of Information

Committee members were requested to supply from their respective Centers all reports dealing with failures of structural materials during the past 5 years. In response, reports were received from Goddard Space Flight Center, Marshall Space Flight Center, Manned Spacecraft Center, Langley Research Center, and Lewis Research Center. Where appropriate, personal contact was made with those persons who were most familiar with the failure analysis. With a few notable exceptions, the reports gave only brief descriptions of the failures and very little information concerning the possible causes and mechanisms of failure. In most cases, the personal contacts were able to provide little additional information. Failures that had a large impact on NASA's programs (e.g., test stand failure of S IVB 503) have been reported in detail, and some have been widely discussed in the open literature. However, sometimes this reporting has not been timely nor in a form that would ensure review by all appropriate members of NASA management.

In order to supplement the information in the failure reports, the Committee enlisted the counsel of research engineers who have been intimately involved in most of the important materials and structures problems of the last decade. The results of the analysis of failure information presented by the Committee are consistent with the experience of these experts. Further, neither the members of the Committee nor their consultants are aware of any major type or cause of structural failure experienced by NASA which is not represented in the analysis. To develop more accurate information would be impossible in most cases because the failed parts are no longer available for examination and in some cases the personnel involved are no longer with NASA.

For the various reasons given above, the Committee judged that further attempts to document the history of NASA's structural failures would not be worthwhile nor would a separate publication of this information be desirable.

Classification of Failures

In order to summarize the failure information in a way that would be helpful in reducing future risks, an attempt was made to develop a "failure matrix" which assigned both a CAUSE and a MECHANISM to each failure. This matrix is shown in table I at the end of this section. The failure CAUSES are defined as follows:

- (1) Defective Material—Material as received from the vendor contained defects not acceptable in terms of the specifications. This would include those

cases where critical cracks or flaws went undetected due to some deficiency in the inspection methods or procedures. The limitations of nondestructive evaluation procedures are discussed in Section II of this report.

- (2) Improper fabrication—Processes and procedures used to fabricate the material into a structure were in conflict with specifications or with recognized good practice to a degree that an unsatisfactory product resulted. Included here would be hydrogen embrittlement introduced by improper plating processes; out-of-tolerance parts, cracks, or flaws introduced by forming operations, etc.
- (3) Poor design—Features of the structure established by the designer were such that inherent weakness was built into the hardware. Included here would be faulty stress analysis, loads applied improperly in respect to the fiber of the material, machining radii too small for the material, known aggressive environments not taken into account, etc.
- (4) Improper use—The structure was subjected to service loads or environments not intended in the design. Also included here is faulty maintenance that led to failure.
- (5) Inadequate knowledge of service conditions—This class contains those cases where the loading or environmental conditions were not defined well enough to produce a satisfactory design. Included would be the effects of unanticipated vibratory loads, aggressive environments, etc. These cases represent a technology deficiency and include costly, serious, and stubborn problems.
- (6) Inadequate materials knowledge—The materials technology was deficient and not even the specialist would have anticipated the problem. There are only a few examples in this class, but they represent our most serious failures in terms of cost and impact on schedules. Included are stress corrosion cracking of titanium in nitrogen tetroxide (N_2O_4) and in methanol. These failures are discussed in detail in Appendix A. The subject of adequacy of materials knowledge is treated in Section II of this report.

The MECHANISMS listed in table I are rough descriptions of what appeared to be the dominant process that eventually led to failure of the structure. It is recognized that these classifications lack the precision that would be desirable, and that many failures result from a combination of factors. Unfortunately, most failure reports do not contain sufficient information to permit a better system of classification. In about 40 percent of the cases, the Mechanism is listed as Other. This class includes those cases reported as tensile overload and those where no mechanism was identified. While most of the failure reports were deficient in definition of the failure mechanism, it should be recognized that an accurate description of the processes leading to failure generally requires an extensive investigation by experts using highly sophisticated equipment.

Conclusions and Recommendations

The Committee submitted the following conclusions and recommendations concerning the availability and adequacy of failure information.

Conclusions:

1. NASA has been relatively free of in-flight failures that could be attributed to deficiencies in materials or structures. Most of the failure reports involved ground equipment, development hardware, or ground testing of flight hardware.
2. There is no standard system for recording failure information within NASA, nor is there any central activity that attempts to analyze failure reports for general trends and then to pass on this information to all concerned NASA activities.
3. The majority of NASA failures were of the type that could be corrected easily with little impact on program cost and schedules. There were, however, a few very serious failures, and outstanding examples of these are given in Appendix A.
4. There is little evidence to indicate that our understanding of material behavior has been deficient in most of the problems encountered. About 78 percent of the failure causes were classified as improper fabrication or poor design. Because many contractors (especially the smaller ones) do not require design review by material specialists, it is likely that the majority of failures in these classes were the result of not having the necessary information at the right time. This matter of data availability is treated in Section III on Communication of Data.
5. While few failures were classified as associated with the mechanisms of oxidation and hydrogen embrittlement, these should not be discounted as unimportant. In the case of hydrogen embrittlement, past experience with aircraft structural parts has shown that failures due to hydrogen embrittlement can be very serious. In respect to oxidation, it would be reasonable to expect that this failure mechanism would assume increased importance in the shuttle program where high strength materials will be operating at high temperatures in the presence of oxidizing atmospheres.
6. Certain high strength alloys were particularly susceptible to failure by a mechanism of corrosion. These include the aluminum alloys, 7075T6 and 7079T6; the stainless steels, AM355 and 17-7PH; and the high strength versions of the common low alloy steels, 4330 and 4340.

Recommendations: The following recommendations are offered for improvement in the failure analysis and documentation procedures. In addition, suggestions are also offered for modifications in the contractual requirements that should reduce the risk of failures in aerospace structures.

1. A single group within NASA should be assigned the responsibility of developing uniform reporting standards for structural failures and recommending failure analysis procedures. This same group should be responsible for the dissemination of this type of information. Section II of this report gives suggestions concerning the implementation of these recommendations by designating a Headquarters Office in OART.
2. In order to make this standard reporting system effective, a review and action procedure should be established by each program office to ensure that the information is transmitted to the appropriate groups and is properly utilized by them.
3. NASA should require from its contractors the following information:
 - a. Evidence that their system of engineering drawing release includes appropriate review by materials specialists
 - b. A failure mode analysis of critical components which is experimentally verified when feasible
 - c. The materials data used in the design and their source

TABLE I: FAILURE ANALYSIS MATRIX FOR 231 FAILURES^a

| Cause | Mechanism | | | | | Cause related percent |
|--|-----------|----------------|------------------------|-----------|--------------------|-----------------------|
| | Fatigue | Corrosion | Hydrogen embrittlement | Oxidation | Other ^b | |
| Defective materials | -- | 1 | -- | -- | 8 | 4 |
| Improper fabrication | 18 | 17 | 5 | -- | 35 | 30 |
| Poor design | 53 | 15 | 1 | 1 | 49 | 48 |
| Improper use | 3 | 8 | 1 | -- | 11 | 9 |
| Inadequate knowledge of service conditions | 5 | 8 | -- | 4 | 2 | 8 |
| Inadequate materials knowledge | -- | 2 ^c | -- | -- | -- | 1 |

^aThe number of failures refer to structural types. In some cases several individual parts may be included in one type.

^bFailure by tensile overload or undetermined

^cVery serious failures with impact on five major program areas (See Appendix A.)

SECTION II: ASSESSMENT OF TECHNOLOGY

The conclusions and recommendations of the Committee regarding the adequacy of the technology in relation to the selection of materials and design methods for aerospace hardware are summarized in this section. Attention was given to the question as to whether the technology existing at the time of the past failures was adequate to have prevented them and whether the present state of technology is adequate to minimize the risk of future failures satisfactorily. In addition, consideration was given to what areas of research need emphasis to improve the methodology of design and materials application in order to provide more efficient hardware with a lower risk of failure than we can now produce. NASA's R&D programs that are designed to provide improved materials (e.g., higher toughness and strength, better oxidation resistance, etc.) were not reviewed. These programs also have the objective of improving structural reliability.

The reports of the Panel members are presented in Appendix B. These give background information in the several areas covered by the Panel studies and present detailed assessment of the technology as well as recommendations for research.

Conclusions and Recommendations

In the following summary of conclusions and recommendations of the Panel on the Assessment of Technology, emphasis has been placed on those areas where NASA's research efforts should be strengthened. Reference should be made to Appendix B for further details and for a description of those research areas where our present efforts appear to be adequate.

Conclusions:

1. There is sufficient understanding among the technical specialists of the various factors which limit the strength potential of high strength alloys to establish significance of these factors in the selection of materials and in the design of hardware. However, this understanding does not yet extend to the point where analytical design methods are available which, by themselves, could adequately minimize the risk of failure of highly efficient complex hardware. This deficiency results from factors such as uncertainty concerning the environments that will be encountered in service; complex loading conditions, such as random fatigue loads and the interaction of temperature environment for which established design methods do not exist; unintentional variations in production and fabrication procedures that can affect the mechanical properties; and the as yet poorly understood practical limitations of NDE methods. Therefore, all members of a technical program team should take into account the following concepts:
 - a. Although the designer must use the best and latest design concepts, a paper design must be followed by simulated service tests of simplified but representative components and finally by simulated service tests of actual hardware.

- b. Structural materials are inherently flawed, and crack growth will occur during service. Therefore, materials should be selected which are compatible with the proven capability of NDE methods to detect cracks, and, where possible, a suitably designed proof test should be used to establish the upper limit on initial flaw sizes. Further, an in-service inspection frequency should be selected which will ensure that cracks can be detected before they reach a dangerous size.
2. Linear elastic fracture mechanics and its associated plane strain fracture toughness values (K_{IC}) can provide a valuable tool for the designer in his fracture control program provided that the basic assumptions of the theory are not violated in its application to the practical problem. Unfortunately, there is an increasing tendency to apply linear elastic fracture mechanics to situations where the basic assumptions are not even remotely approached. Under some circumstances such applications can increase rather than reduce the risk of failure. For further details see Appendix B, Design Methods.

In this connection it should be noted that DOD has requested the National Materials Advisory Board of the National Research Council to establish an ad hoc Committee on the Application of Fracture Prevention Principles to Aircraft. One of the objectives of this Committee will be to define more clearly the role of elastic fracture mechanics in aircraft design. W. F. Brown, Jr., of NASA-Lewis is a consultant to this Committee.

3. Generally, the past failure problems have been related to a lack of utilization of existing knowledge during the material selection, design, and testing phases of the hardware programs rather than to an absence of the necessary information.
4. Our materials and structures research programs are at present reasonably well balanced and have made major contributions to the technology in all pertinent areas of materials research and structural analysis including fracture mechanics, fatigue, and corrosion. In fact, many of the major contributors to these areas are at NASA Centers. It is vital that support for these programs be continued at present levels if we are to avoid a set of new and potentially more dangerous failures in our future aerospace hardware.

Recommendations: The following critical areas require an intensification of our research efforts:

1. Standardized test procedures should be developed for the determination of fracture properties and stress corrosion resistance of metallic alloys. These methods would supplement the already available ASTM Standard for determining plane strain fracture toughness (K_{IC}). For further details see Appendix B, Fracture Toughness, Selection of Materials and Stress Corrosion, Selection of Materials.

2. Long range plans should be established by NASA and DOD to provide systematic data on fatigue, fatigue crack propagation, and fracture properties of structural materials. These plans should provide for continuity of support of such data-generating programs.
3. NASA should conduct and sponsor research leading to improved design procedures for combatting fatigue and improving fracture tolerance in aerospace structures. These procedures should include: 1. computer systems for handling large volumes of empirical data and 2. reliable methods for conducting fatigue evaluation tests of complete structures within practical time schedules.
4. NASA should develop improved methods for anticipating and monitoring service loadings in individual aircraft.
5. Additional research is needed to define clearly the limitations of conventional NDE procedures in terms of their sensitivity to actual cracks and to develop improved techniques. This very important area requires a focal point within NASA which would coordinate research activities and establish a reference file of information concerning the characteristics of available equipment. For further details see Appendix B, Nondestructive Evaluation.
6. Additional research is needed in the area of gaseous hydrogen embrittlement with particular emphasis on the effects of hydrogen pressure, temperature, and loading rate on the tendency to delayed failure in the presence of cracks. For further details see Appendix B, Hydrogen Embrittlement.
7. As indicated in Appendix B, Composite Materials, the rational design of highly stressed hardware made from composites requires additional information on mechanical properties derived from standard tests, better structural analysis procedures, and the development of nondestructive evaluation techniques suitable for detecting manufacturing flaws.

SECTION III: DOCUMENTATION AND COMMUNICATION OF INFORMATION

While the causes and mechanisms of NASA's structural failures were not always clear, the Committee found that in the majority of cases the problems encountered were fixed by application of technology that existed at the time the structures were designed. The conclusion, of course, is that the designer or project engineers did not have access to the necessary information or for some reason did not apply the knowledge at hand. The Committee, therefore, examined the adequacy of documentation and communication of technical information related to the selection of materials for aerospace structures and for the design of such structures. Included in this information are failure analysis, mechanical and physical properties of structural materials, and the influence of fabrication processes and service conditions on these properties, as well as methods of structural analysis.

The Committee gave consideration to the following topics:

- (1) Sources of information
- (2) Accessibility of information
- (3) Discipline in use of information

The following is a summary of the Committee's conclusions and recommendations. More detailed information is given in Appendix C.

Conclusions:

1. There are several very useful and nationally recognized handbooks and Information Centers which provide information on materials properties and problem areas. Some of these activities have been in existence for over a decade. Most of their support is supplied by DOD with a relatively small amount coming from NASA. They have been under continuous pressure from the Office of Defense Research and Engineering to become self-supporting, but their DOD funding has declined gradually over the past few years until at present it is about two-thirds of the 1969 level. The present plans of DOD are to require that the Information Centers obtain at least 50 percent of their funds from sale of their services during fiscal 1972 or all DOD support will be withdrawn. This requirement appears to be unrealistic in view of the basically limited market for such services which presently is further reduced by the depressed condition of our aerospace industry. Further cuts in their support would seriously reduce their effectiveness and their elimination would have a substantial adverse impact on NASA and DOD efforts to increase the integrity of aerospace structures (see Appendix C, Sources of Information).
2. Both handbooks and Information Centers would be more effective and efficient if reports generated from NASA or Air Force research and development activity on materials would be automatically distributed to the pertinent handbook or Information Center activity (see Appendix C, Accessibility of Information).

3. Neither the NASA RECON nor the DDC computerized literature searching facilities are able to identify report titles containing alloy property data through a code relating to common alloy types. Therefore, these facilities are of marginal use to the materials engineer and designer.
4. The risk of failure of aerospace structures and the cost of their development could be significantly reduced if NASA would improve its system for documentation and dissemination of pertinent technical information throughout both its program offices and contract operations. At present, NASA is weak in this area, in part because there is no central group charged with the responsibility of assisting the program offices in identifying the sources of pertinent information.
5. It is very important that the risks of failure be assessed early in the design phase of hardware development by appropriate materials and structural analysis specialists. Unfortunately, in most cases these specialists are not able to quantify the failure risks and their recommendations are balanced against direct calculations of performance and weight. Thus, management is faced with a difficult problem of judgement, and, to be most effective, this should be made well before performance and weight are fixed. Otherwise it is likely that the measures recommended to reduce failure risks will result in decreases in performance or increases in weight which are hard to take when the program is well along.

Recommendations:

1. NASA should increase its support (with other Government agencies) of selected materials information services that summarize or accumulate and analyze mechanical and physical property data on metals, composites, and plastics of particular interest to the aerospace industry. Examples of activities of this type that should be supported include:
 - a. The Aerospace Structural Metals Handbook
 - b. MIL-Handbooks 5, 17, and 23
 - c. Defense Metals Information Center
2. The NASA RECON system should be so modified that searches by alloy type would be possible. This could be accomplished by the introduction of a systematic coding system for metallic alloys and other structural materials. The alloy coding system used in the Aerospace Structural Metals Handbook might be suitable for metallic alloys and if used would greatly increase the usefulness of the RECON system to the handbook editors.
3. NASA should arrange to place the Air Force Information Centers and handbook activities on automatic distribution for NASA internal and contractor reports dealing with materials properties and structural analysis.

4. NASA should develop a rational plan to apply the best technical judgement to each project on a timely basis and establish controls that ensure its execution. This plan should include:
 - a. Introduction of materials specialists and structural experts into the project at the planning stage before performance requirements are fixed
 - b. Development of a "Materials Selection Guide" which identifies those material conditions which are particularly sensitive to strength limiting factors (e.g., stress corrosion, small flaws, fabrication processes, etc.) and adoption as part of contracts
 - c. Justification by contractor of selection of a sensitive material and how this sensitivity will be overcome in the proposed application
 - d. Identification within NASA Centers of materials application and structural analysis specialists who could assist the program offices during the design phase of critical components and who could, when appropriate, serve on a Materials Review Board
5. NASA should contractually require the following:
 - a. That failure mode analysis be conducted for all major failures and that the derived information be analyzed and incorporated into a report suitable for distribution to all pertinent organizational segments of NASA
 - b. Evidence that a meaningful fracture control program is being developed by the contractor early in the design phase of the project
 - c. Evidence that material specialists have been consulted in the drawing approval chain for all critical parts
6. It is recommended that an office be designated within OART (possibly in the Materials and Structures Division). This office would, with the assistance of appropriate Center representatives:
 - a. Co-operate with other Government agencies in supporting information collection and dissemination services
 - b. Act as a clearinghouse for failure analysis reports
 - c. Expand efforts in design criteria
 - d. Disseminate to project offices and contractors appropriate educational material concerning information sources and methods to avoid failures of the type experienced in the past
 - e. Develop Materials Selection Guidelines and identify those persons in NASA Centers who are specialists in materials application and structural analysis

APPENDIX A: Review of Failure Reports

Panel Members:

Chairman, R. E. Johnson, NASA Manned Spacecraft Center

R. R. Heldenfels, NASA Langley Research Center

W. R. Lucas, NASA Marshall Space Flight Center

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APPENDIX A: REVIEW OF FAILURE REPORTS

by Robert E. Johnson
NASA Manned Spacecraft Center

The failure analysis found two types of structural failures where the cause could clearly be classified as "Inadequate Materials Knowledge." These were associated with the stress corrosion of Apollo titanium alloy tanks in the presence of pure nitrogen tetroxide and anhydrous methanol. These failures seriously impacted five major program areas both in terms of schedule and cost. Experiments carried out after the failures were encountered indicated that stress corrosion cracking of titanium alloys can occur in the presence of certain organic fluids and pure N_2O_4 if even very small surface discontinuities (such as a rough machined surface or surface scratches) are present. This was a fact unknown to the experts in the stress corrosion behavior of metallic materials. A brief review of these two failure types follows.

Titanium and N_2O_4

Tests were performed by the contractor to demonstrate compatibility before the combination of 6Al-4V-Ti was approved as a pressure vessel material for use in Apollo systems. These tests included stressed samples in contact with oxidizer procured to the Government specification covering N_2O_4 (MIL-P-26539A). In June 1964 two large Apollo Service Propulsion System titanium alloy tanks successfully passed 30-day tests while pressurized with N_2O_4 . All the test data indicated compatibility of the alloy with the oxidizer.

Unknown to NASA and their contractors, the U.S. Air Force was working with the producer of N_2O_4 to standardize its composition, and a manufacturing process-change was made by the producer on May 20, 1964, which resulted in a higher purity product by eliminating certain products including nitric oxide (NO). Since the MIL-P-26539A specification did not require analysis for NO or the reporting of the amount present, the change was not detected by NASA contractors until after stress corrosion cracking failures occurred in ground testing an Apollo RCS tank in January 1965. The failure analysis and subsequent test programs are well documented in the literature and in Apollo reporting systems. Since Apollo, Saturn, Lunar Orbiter, and USAF hardware were involved, and interagency, intercenter committee managed the test programs, which resulted in a NASA specification (MSC-PPD-2) controlling the composition of N_2O_4 and specifying limits on the NO content that would prevent stress corrosion cracking of the titanium alloy.

The Apollo, Saturn, and Lunar Orbiter programs are now using the new NASA-grade N_2O_4 , and no further failures have been encountered. This problem is an example of the high level of control that is required when sensitive metal conditions are exposed to potentially aggressive environments.

Titanium and Methanol: In October 1966, a pressure check on the Apollo Service Propulsion System was being performed at North American Rockwell using methyl alcohol (methanol) as the pressurizing fluid instead of the toxic and hazardous

propellants that the tank would contain during service operation. This procedure and fluid were used on earlier spacecraft without incident, but during this test a leak developed in the 6Al-4V-Ti fuel tank. The leak occurred in the weld heat-affected zone, and subsequent analysis revealed no material defects other than a weld mismatch, which resulted in a sharp notch effect on the inside surface of the cylinder. At that time, the methanol was not suspect because of its previous uses and because no reports of incompatibility between titanium and methanol existed in the literature. Methanol was used because it matched the propellant in density and viscosity and because it was easily removed from the system.

During the next spacecraft test, one of the titanium alloy tanks failed catastrophically, resulting in extensive loss of hardware and damage to the test facility. Metallurgical examination indicated stress corrosion cracking was the cause of failure. Subsequent tests showed the extreme sensitivity of titanium alloys to dry methanol containing trace contaminants of chlorides (in part-per-million range).

Extensive searches of technical literature revealed only one earlier report of titanium-methanol incompatibility, and it involved methanol with small additions of hydrochloric acid. As a result of this new material problem, NASA, its contractors, and the Defense Metals Information Center issued immediate reports and called a special symposium to explain details of the problem as they were known at that time. Examples of documentation of the subject are NASA TN D-3868 (Feb. 1967) and DMIC Memorandum 228, March 6, 1967.

APPENDIX B: Assessment of Technology

Panel Members:

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APPENDIX B: ASSESSMENT OF TECHNOLOGY

Detailed reports of the Panel on Assessment of Technology are presented herein. Also included are reports in two areas that were prepared for the Panel by specialists at NASA-Lewis Research Center. The Panel considered the adequacy of technology in terms of those material characteristics which are known to be of critical importance in the design of aerospace structures; namely (1) cycle dependent fatigue, (2) fatigue at high temperatures and thermal fatigue, (3) creep, (4) fracture toughness, (5) stress corrosion, (6) hydrogen embrittlement, (7) oxidation, and (8) subcritical flaw growth. In addition, reports are included on the important subjects of nondestructive evaluation (NDE) and on composite materials. This latter subject will assume increasing importance in the design of future space vehicles and was the only area of materials development considered by the Panel. It should be noted, however, that NASA has a large R&D effort designed to provide improved metallic alloys and that these programs also have the object of improving structural reliability. Where appropriate, the following topics were considered under each of the above headings:

- (1) Data for material selection—Have the necessary data been obtained which will permit the designer to select the best materials for resistance to failure?
- (2) Data for hardware design—Are design data available which define the expected range of pertinent material properties with a prescribed level of confidence?
- (3) Material specifications—Have specifications containing these statistically determined material properties been developed which will permit their use in the design of critical hardware?
- (4) Design methods—Are methods available which will permit a designer to incorporate the most pertinent material property data into the design?

The Panel solicited assistance from experts at NASA Centers in the areas of elevated temperature fatigue, creep, oxidation, and composite materials, and their reports are included in this appendix. In preparing their reports, the authors were requested to address the specific question, "What direction should be taken by further research in a particular area if the purpose is to provide the designer with better means for reducing the risk of failure in aerospace hardware?" Answers to this question appear in the form of recommended actions at the end of each appendix section.

CYCLE DEPENDENT FATIGUE

by Herbert F. Hardrath
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Background

Research and development testing on fatigue have led to a satisfactory appreciation of the host of parameters that determine fatigue life in service. From this activity have come many qualitative rules of thumb that are useful to the designer. However, quantitative methods are not yet available for designing efficient structures that are safe from fatigue failure in service.

Thus, current designs are accomplished through a combination of judgement, extrapolation from past experience, empirical rules, ad hoc testing, and careful inspection and maintenance programs. Because of the many uncertainties involved in each step, many structures are constructed with damage-tolerant features to reduce the likelihood of catastrophic failures.

Major Parameters

The fatigue phenomenon is critically dependent upon four major parameters and upon synergistic interactions among them: the material used, the configuration of parts, the loading experience, and the service environment (chemical and thermal). A brief comment on each serves to illustrate the complexity of the problem.

Fatigue behavior of a material is dependent upon many factors, such as the life for a given stress level—a relation that is different for various combinations of mean and alternating stresses; the notch sensitivity—which is generally greater for materials with high static strength; and the susceptibility to corrosion—which also is greater for many high strength materials. The characterization of this behavior to the extent needed to choose materials requires at least several dozen tests for each variable. To establish the characteristics to the level needed for quantitative predictions will require many times that number. Because no quantitative rules are available to relate these characteristics to each other and to other material properties, no simple measure of fatigue adequacy of a material is available.

Structural parts inevitably contain holes (changes of cross section and joints), each of which introduce local stress concentrations. In principle, such stress concentrations must be evaluated accurately for each such structural feature. An error of 10 percent in the estimated local stress could well represent an order of magnitude error in life of the structure in service. Further, fatigue life is dependent upon the absolute size of a part. Because this "size effect" is not adequately understood, tests of scaled specimens can produce significant errors. Consequently the fatigue adequacy of particular configurations must be verified by tests of full-sized components.

In service, structural parts are almost always subjected to very complex loading histories caused by maneuvers, gusts, acoustic excitation, landings, taxiing, and other sources. Each of the loading excursions contributes to the total fatigue "damage"

inflicted on the parts. Although simple rules are available for assessing the cumulative effects of complex loading, the predictions by these rules are recognized as being subject to gross errors. Again, tests in which such loadings are simulated in considerable detail are quite often required.

Aerospace structural parts are subjected to a variety of hostile environments that further complicate the designer's problem. Corrosion due to weather, exhaust gases, food and lavatory spillage, and salt from runways can all have a severe influence on fatigue behavior. Such influences are rarely simulated in evaluation tests, but raise more uncertainties concerning predicted lives. Similarly the temperature of the operating environment can have a significant influence on life, particularly when the temperature is high enough to introduce creep. This behavior is discussed in more detail in the following section on Fatigue at High Temperatures and Thermal Fatigue.

Improvements Through Research

Systematic research that identifies the role played by each of the parameters cited earlier is in progress in many laboratories. Because of the very large number of variables within each major factor, a tremendous number of tests would be required to provide sufficient design data on which to base a structural design. Fatigue research conducted in NASA laboratories at Langley and Lewis is devoted to establishing better quantitative rules that will aid the designer to do his job with fewer ad hoc tests. This research is generally recognized to be among the most significant being conducted in this area of engineering. The following are examples of notable advances that have been made:

- (1) Development of quantitative methods for anticipating stresses near discontinuities even when the stress exceeds the yield strength
- (2) Identification and rationalization of systematic nonlinear trends in cumulative damage
- (3) Identification of the systematic effects introduced by various loading sequences
- (4) Demonstration of deleterious effects of outdoor environment
- (5) Investigation of the fatigue behavior of titanium alloys as influenced by the operating environment of the supersonic transport
- (6) Separation of the fatigue process into a crack initiation and crack propagation phase and application of quantitative treatment to both

Many of these results are helping to shape the philosophy of designing and testing to avert fatigue failures in service. However, large numbers of effects and combinations of parameters must still be studied systematically before an overall quantitative design concept can be developed. Much more research directed toward such engineering solutions is needed.

As indicated previously, research to improve materials and their behavior has not been considered deliberately by this committee. However, very large numbers of simple fatigue tests (usually rotating beams) are conducted for this purpose. Although under some circumstances such tests are useful for selection of materials, the results are rarely of use to the designer in establishing permissible stress levels in complex hardware.

Design Philosophy

In view of the complex nature of the fatigue problem and the inadequate state of design rules for preventing fatigue problems in service, designers frequently incorporate "fail-safe" or "damage tolerant" features in primary structures to avert catastrophic failures in service. Two general features are usually employed: the structural components are configured in such a way that a crack that leads to failure of a given part does not precipitate failure of the whole, and materials and stress levels are chosen so that fatigue cracks grow at a rate slow enough to be detected by prescribed inspection procedures.

The fracture concepts discussed in the section on Fracture Toughness are basic ingredients to fail-safe design. However, fracture concepts must be developed to apply to practical materials (most of which display considerable ductility) in realistic complex configurations. In addition, the behavior of fatigue cracks under complex load histories must be thoroughly investigated. Until these extensions of fracture mechanics are made, this design approach is also dependent upon judgement and extrapolation from previous experience. Fail-safe tests are frequently performed on full-scale hardware to satisfy certification requirements. NASA personnel play a leading role in investigating the behavior and in developing the necessary design rules.

Partly because fatigue design technology is inadequate and partly because the available technology and its limitations are not understood adequately, designers too frequently make mistakes in judgement. The extreme pressures to produce lightweight structures at low cost may force these judgements to be made on the unsafe side.

Conclusions:

The large number of parameters influencing fatigue behavior, the complexity and variety of details that comprise a practical structure, the complexity of the service environment and the statistical variability of each of these factors render the analytical prediction of fatigue life impossible at present. Improved quantitative rules are needed to cope with many facets of the problem.

For the present, empirical rules and much ad hoc testing must be employed to produce designs that are efficient and have adequate fatigue life.

Damage tolerant features must be incorporated to reduce the likelihood of catastrophic failures in service.

Adequate structural integrity depends critically on monitoring usage and careful inspections for fatigue damage.

Recommended Actions:

1. Conduct continued research to produce quantitative design rules that account adequately for the many parameters affecting fatigue behavior of practical structural configurations operating under representative loadings in practical environments.

2. Develop automatic computer systems for systematizing and condensing huge quantities of fatigue data into a form useful to designers.
3. Sponsor the generation of additional data on fatigue behavior, on fatigue crack propagation and residual strength as needed to characterize the behavior of key materials for aerospace structural applications.
4. Develop improved methods for anticipating and monitoring service loadings in individual aircraft.
5. Develop methods of assuring adequate resistance to fatigue crack propagation and adequate residual static strength in the presence of damage for practical hardware.
6. Develop adequate methods of inspecting for damage in real hardware in service and means for setting inspection intervals.
7. Develop reliable methods for conducting fatigue evaluation tests of complete structures within practical time schedules.

FATIGUE AT HIGH TEMPERATURES AND THERMAL FATIGUE

by J. C. Freche and S. S. Manson
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Background

At high temperatures, above 0.4 or 0.5 of the absolute melting point, materials under sustained load will continue to flow plastically or creep, whereas they would not at lower temperatures. The process of failure under repeated cyclic stressing at these high temperatures thus changes from the usual cycle-dependent (and time-independent) failure process of low temperature "fatigue" to include the time-dependent effects of creep, relaxation, and even metallurgical structure changes.

Often the cyclic stresses or strains are not introduced by repeated mechanical loading, but rather they result from temperature gradients in the parts induced by temperature cycling of the device. The failure mechanism resulting from cyclic stresses introduced by thermal gradients is called "thermal fatigue" and greatly complicates the problem of design. If the designer were to attempt to calculate the cycles to failure as a basis for his design, he must be able to go all the way from the expected temperature changes in the environment through the steps to crack initiation, as follows:

| Calculation | | Material properties |
|----------------------------|---|---|
| Environment | } | |
| Metal temperature | | — Conductivity, specific heat |
| Cyclic strain | | — Thermal expansion coefficient |
| Cyclic stress | | — Elastic modulus, yield strength, creep rate |
| Cycles to crack initiation | | — Ductility, tensile strength, creep rupture strength |

In addition, every time he considers a material property in this process, he must deal with a situation wherein the properties of his material are changing with temperature.

We are just beginning to obtain an understanding of the problem. Much of the fatigue work at Lewis, for example, is directed toward obtaining the necessary understanding of the complex factors involved and, of course, devising means for predicting material behavior under such complex loading conditions in advance of service. A reasonable understanding exists of the problem of isothermal, high temperature fatigue. For preliminary design purposes the "10 percent rule" (ref. 1) provides a good rule of thumb for predicting uniaxial low cycle fatigue behavior in advance of service, keeping in mind the limitations as discussed in reference 1. For more complex loading conditions involving varying temperature and stress, or for applications to metallurgically time and load sensitive materials, a linear damage life-fracture rule, together with the use of a cyclic creep rupture test (refs. 2 and 3), provide the designers with useful guidelines in predicting material behavior. However, much more research and

development work is required for a better understanding of the interaction effects of the many variables involved, such as the role of frequency, compressive stresses, mean stresses, hold times, and load versus strain cycling. Next, the validity of the application of these techniques to aerospace hardware items, such as turbine blades, must be verified under simulated engine operating conditions. Since the problem of high-temperature fatigue in its broadest sense involves a combination of many individual factors such as fatigue, thermally induced stresses, mechanically applied stresses, and creep, its solution is dependent in part upon our understanding of both creep and fatigue mechanisms. Consequently continued research in each of these areas, together with research directed at the total problem is a necessity.

Selection of Materials

The tests being used for isothermal high temperature fatigue have been fairly well agreed upon by many of the laboratories in this country. These laboratories use electronically controlled equipment for conducting both load cycling and strain cycling tests. The ASTM E-9 Committee on Fatigue is involved with testing procedures, and its recommendations will eventually result in standards regarding test procedures. A recent ASTM Special Technical Publication (ref. 4) describes the latest techniques. Isothermal high-temperature data may be found in a number of publications and handbooks. Some of the better sources of data compilation are contained in references 5 to 7. Additional data can also be found in many reports in the open literature. However, relative to the availability of room-temperature fatigue data, the isothermal high-temperature fatigue data are limited.

In the area of thermal fatigue (fatigue resulting from cyclic variation of temperature) a variety of tests are being used, usually depending upon the preference of the investigator. These include fluidized bed tests (sometimes involving Glenny-type specimens; see refs. 8 and 9) and completely restrained thermal cycling. The E-9 Committee is also considering recommendations in the area of thermal fatigue testing. As to availability of thermal fatigue data, these are even more limited than isothermal high-temperature fatigue data. Also, there is little correlation possible of the existing thermal fatigue data because these data were generally obtained in different tests and under widely different test conditions. A limited compilation of thermal fatigue data (in the sense of ranking high temperature materials with respect to thermal fatigue resistance) has been obtained by Glenny et al. (refs. 8 and 9). Also in this area, considerable amounts of data are being generated both at Lewis and under Lewis-sponsored contracts such as at IITRI (ref. 10). Here extensive thermal fatigue testing of virtually the entire gamut of superalloys, including the most advanced, is being done both to provide a ranking of their thermal fatigue resistance and to provide data for our analytical studies. These data will, of course, become available in NASA and NASA-contractor reports.

Data for Hardware Design

In addition to such data as have been described, there are undoubtedly data in the files of industrial users of high temperature materials. To be used, they must be

considered in the light of their possible limitations for the particular design application. As to statistical aspects relative to both high-temperature isothermal, low cycle fatigue and thermal fatigue data, there appears to be a fairly high degree of data reproducibility if the material processing and testing conditions from specimen to specimen are kept the same. This is true to a much greater degree than for high cycle fatigue data where flaws in the material can be instrumental in producing strain concentrations which can markedly exceed the relatively low externally applied nominal strain and cause drastic reductions in life compared with a specimen without flaws. Thus, although large amounts of data in these areas (particularly thermal fatigue) are not available, the need for data in the amounts that would be required to establish a fatigue limit, for example, in a statistically satisfactory manner, is not so great.

For low-cycle strain cycling fatigue in the creep range, and for thermal fatigue involving temperatures in the creep range, additional data now not commonly obtained will be required. Notable among these are short-time creep-rupture properties, tensile properties at high strain rates, and relaxation properties. Current practice is to use extrapolation procedures to determine the short-time (1 hr or less) properties required in the calculations; however, there is no reason why the data could not be directly generated for the materials of interest. Tensile and creep properties at high strain rates and relaxation properties are required because both factors enter into the determination of stresses at the strain rates developed during a thermal fatigue cycle. Data of this type must be obtained on materials of interest, particularly materials involving time-temperature instabilities. Also, methods must be established for correlating such data so that they can be represented in concise form and for extrapolation to conditions other than those used in the particular tests conducted during data generation. Possibly the time-temperature parameter concepts previously used to correlate creep and rupture data can be applied for this purpose.

Materials Specifications

No specifications for thermal fatigue resistance are called for in ordering materials from a producer. The fluidized bed test is the closest to what may be considered a standard today. The results of testing Glenny-type specimens (1-5/8 inch diameter with a 0.010-inch edge radius) in fluidized beds are sometimes included in a tabulation of data by producers of high temperature alloys (notably the International Nickel Company). A number of these facilities exist throughout the country, and comparisons of thermal fatigue resistance among alloys is sometimes possible.

Insofar as isothermal high temperature fatigue specifications are concerned, the cost of conducting these tests usually precludes their insertion into specifications. They may, however, be called for as a final means of judging whether a material lot is suitable (i. e., if it falls short in other conventionally asked for requirements such as tensile strength, grain size, etc.).

Design Methods

Design methods that have been previously described, such as the "10 percent rule" for isothermal, high temperature fatigue, are readily applicable by designers.

Further detailed procedures for other aspects of design for high temperature service are described in various texts such as reference 11. For the more complex loading conditions, the techniques are not well established. For most design applications, the input to design problems is not always well defined. (This is particularly true for the temperature distributions.) Consequently critical tests are usually needed for complex hardware to ensure suitable design capability. However, as the technology advances, certain analytical procedures can be used to replace direct testing. Creep, strain-rate effects, and relaxation can be incorporated into the equations of equilibrium and compatibility which describe the thermal and mechanical loading processes. The measured creep and relaxation properties can be incorporated into the stress-strain relations to permit more accurate solutions. The basic methods would be the same as those described in references 2 and 10, but more accurate determination of stresses and strains would be possible by this approach.

Conclusions and Recommendations

Deficiencies in the technology: From the standpoint of material selection and component design, the following deficiencies can be recognized in the technology base:

1. A more complete understanding must be obtained of the interaction effects of the many variables involved in complex high temperature cyclic loading applications. This is necessary so that techniques, capable of accurately predicting material behavior of parts subjected to high temperature fatigue in its broadest sense, can be developed.
2. Additional data, particularly thermal fatigue data, for the newer, high temperature materials are needed to assist designers in making material selection.

Recommended actions:

1. As a first approximation to estimating isothermal, high temperature, low cycle fatigue life, the 10 percent rule is a useful approach. It is useful as a guide to designers when complete data on stress and strain history cannot readily be obtained or when simplified analysis is the only possibility open to the designer.
2. For somewhat more complex loading conditions involving varying temperatures and stress, or for application to metallurgically time and load sensitive materials, a linear damage life-fraction rule, together with the use of a cyclic creep rupture test, will provide designers with useful guidelines in predicting material behavior.
3. To obtain a better understanding of the interaction effects of the many variables involved in the very complex high temperature cyclic loading applications, a number of studies should be made. These include determination of fatigue crack initiation and propagation rate factors and the manner in which they are influenced by the ratio of minimum to maximum stress, variable amplitude loading, hold time, geometry, and environmental factors, including high temperature for various

engineering materials, as well as the determination of strain rate and relaxation effects for engineering materials at high temperatures. These factors can then be incorporated in design practice and significantly advance the science of fail-safe design procedures, the practicality of which has already been augmented by the development of Fracture Mechanics Laws for crack growth.

4. More thermal fatigue data should be generated for high temperature materials using the highly efficient fluidized bed method that has been employed in the NASA sponsored investigation at IITRI.

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CREEP

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Background

Present theories of the mechanical behavior of metals and alloys are inadequate to describe quantitatively the behavior of a real material during plastic deformation. However, empirical formulations have yielded practical methods for correlating material behavior and predicting the long-time properties with reasonable accuracy. The expressions are concerned mainly with the strain-time relation, the effect of temperature, and with the dependence on stress. When used judiciously and with a realization of the magnitude of possible errors, they furnish readily applicable techniques for summarizing many data in convenient form for purposes of comparison and for improving the accuracy of extrapolations. Some of the parameters, such as the Larson-Miller and the Manson-Haferd parameter, have become integral parts of the materials engineer's and designer's lexicon. These, as well as other time-temperature parameters are adequately described in textbooks and design manuals. Shorthand methods of applying the parameters are often available in nomograph form from suppliers of materials.

In the case of uniaxial creep, practical engineering has developed from useful, simple laws which have an extensive generality and a close relation to an underlying theory. This is not to say that further research and development work is not needed in the area of creep. Certainly more work is required to understand fully the roles of the effects of atmosphere, size and shape, and temperatures above those at which oxidation occurs. Special effects associated with notches have been observed and only partially explained (i. e., effect of notches on the creep rupture life of nickel-base sheet in the 1000° to 1200°F range). Also, although biaxial tension-tension (pressurized cylinders) has been extensively investigated, further work under other multiaxial loading conditions is needed. Because of the general complexity of the latter type of investigations, such investigations should be more of an exploratory nature. If pronounced effects are found, these studies should be pursued. For design of aerospace structures, more data and a better understanding of primary (first stage) creep is desirable. For example, upon reentry, the sudden incidence of high temperature can lead to first stage creep in some structural members. How to predict the effect of repeated conditions of this kind on the primary creep curve of various materials is of great importance to the designer.

Of course, further work should be and is being done to check the validity of the various time-temperature parameters in predicting long-time creep-rupture life. Along this line, there is a special ASTM Committee that has been formed for the express purpose of setting up standards for use of time-temperature parameters. The committee consists of S. S. Manson (Lewis Research Center), W. E. Leyda (Babcock and Wilcox), R. M. Goldhoff (General Electric), and George Smith (Consultant to Materials Properties Council). Also, in this latter connection, a station-function analysis proposed by Manson and coworkers (ref. 1) can provide a basis for this

evaluation. The approach relies on a generalization of the concept of time-temperature parameters in which higher temperature is substituted for longer time in generating the data from which extrapolations are made. By introducing a station-function procedure, the method applies an optimization procedure for seeking out the most pertinent parameter whether or not it is among those in common use.

Selection of Materials

Test methods for uniaxial creep are well established, and equipment is generally available that is adequate for obtaining data for design purposes over the entire useful temperature spectrum. Test methods and techniques are well defined (recommended ASTM practice).

A considerable amount of creep data exists, but these data are frequently buried in the archives of companies that use the materials in question. These come to light occasionally as a result of a particular development program which the company wishes to publicize, or because of specific requests for information, or as incidental parts of reports which deal with major developments such as the SST which require the use of advanced materials. For example, engine manufacturers, when they have a proprietary interest, develop more data for an alloy than the original alloy producer. A case in point is MAR-M200, used by Pratt and Whitney as a bucket material. This alloy was used in the development of controlled solidification casting techniques and showed substantial strength and ductility increases when directionally solidified. Pearcey, Ver Synder, and others have written at least a half dozen papers in which MAR-M200 is compared with other materials. Actually Pratt and Whitney generated much of the data on the original alloy to use as a base in comparisons with the directionally solidified versions. Sometimes reports by contractors (such as Pratt and Whitney or General Electric) made to contracting agencies contain design data obtained with advanced materials (i. e., creep data up to 10000 hr for materials such as IN-100, Waspaloy, TD-nickel). Thus, it is our experience that a substantial amount of creep data exists even for advanced materials.

Much of the data obtained by industrial organizations probably never is made available for general use. There are, however, a number of positive steps being taken which project a somewhat brighter picture and which indicate that a great deal of material is available and much more is being obtained. An important case in point is the Aerospace Structural Metals Handbook. This is constantly being up-dated to include not only the latest alloys, but also additional properties on already listed materials. In this handbook there is a Special Considerations Section associated with each material, which, if studied by designers, would guide them in its use and serve as a useful supplement to the creep data that are provided. Not to be overlooked are the supplemental DMIC reports which frequently contain creep data on even the most advanced materials. These sheets appear every few months. Some of the comprehensive listings are those of references 2 to 4.

Data for Hardware Design

Much of the creep data, especially for the newer materials, is not statistically founded, but scatterbands and sufficient data have been obtained on most old-line materials to establish minimum properties. These creep data are available in the open literature, from DMIC, in references 2 to 4, and in some cases from the alloy producer. Data on strain-rate effects and on relaxation are very limited, however, especially for the new materials of current interest.

Specifically in the area of creep, the Metal Properties Council, which is a joint activity of ASME, ASTM, ASM and various industrial groups, is currently sponsoring the acquisition of long-time data (up to 100000 hr) for several aluminum alloys. These data are being obtained not only to characterize the materials thoroughly, but also to check the validity of extrapolation procedures and various time-temperature parameters. Also, the Advisory Group for Aerospace Research and Development of the North Atlantic Treaty Organization (AGARD) has instituted a worldwide program to obtain creep data on selected high temperature materials. One of the purposes was to determine the degree of agreement among data obtained by participating laboratories and establish statistically reliable data.

Materials Specifications

Creep requirements are included by users of such materials in a number of cast as well as wrought high temperature alloy specifications. These are negotiated and agreed upon by both consumer and supplier. For example, a Pratt and Whitney specification for B-1900 (PWA-663), a nickel-base superalloy, calls for certain minimum rupture lives at specified test conditions. It also calls for a minimum elongation measured not more than 2 hours before rupture. Such requirements are of course documented in materials specifications of major users such as Pratt and Whitney and General Electric. Discussions with suppliers of superalloys indicate that such requirements are appearing in all the recent specifications submitted by purchasers. It is interesting to note that in discussing specifications with a representative of Wyman-Gordon, a major supplier of high temperature materials to turbojet engine manufacturers, it was pointed out that superalloys are not purchased according to Aerospace Materials Specifications for engine applications because these specifications are not sufficiently restrictive.

Design Methods

As discussed previously, in considering the technology there are a number of design procedures and methods available which can enable the average designer to proceed with rational hardware designs. These are available in many books and publications. Among those that provide treatments of many facets of design involving creep are references 5 to 9. The basic equations for equilibrium and compatibility in creep problems are well known (e.g., refs. 5 and 6); however, more sophisticated stress-strain relations, taking into account plasticity, strain-rate effects, and relaxation effects, are required to obtain accurate calculations of stress and strain, both

of which appear to be of importance in thermal fatigue and other creep applications. New techniques may be required for accurate solution of the resulting equations, for example, the finite-element approach.

Conclusions and Recommendations

Deficiencies in the technology: From the standpoint of material selection and component design the following deficiencies can be recognized in the technology base:

1. Availability of long-time creep data (30000 to 100000 hr) is limited. This is particularly true for the materials of current interest.
2. Data on strain rate effects and relaxation are very limited for virtually all materials.
3. Data under multiaxial loading conditions other than biaxial tension-tension is required.

Recommended actions:

1. Additional long-time creep data acquisition such as that currently being sponsored by the Metal Properties Council should be encouraged.
2. Check the validity of extrapolation procedures, that is, determine how short-time data can be used in the most effective and reliable manner to predict results of time-consuming tests. In this connection, further participation of NASA in, and continuance of, the activities of the High Temperature Creep Testing Program of the AGARD Structures and Materials Panel is recommended. Also, the NASA station-function minimum commitment approach, in which the "real behavior" of the material is used to establish the functional relations that apply to that particular material, should be further evaluated as a means of more confidently permitting short-time data at high temperature to be used for long-time extrapolations.
3. The interrelation of strain rate effects and relaxation should be investigated with a view toward developing a workable hypothesis for accounting for prior stress, temperature, and strain history in life prediction. A program of this type is being initiated at the NASA Lewis Research Center.
4. Exploratory investigations to develop creep data under complex multiaxial loading conditions should be initiated to determine if any pronounced effects occur that are not predictable by existing theories.

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FRACTURE TOUGHNESS

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Background

In the context used here, the term fracture toughness refers to a measure of a metallic material's resistance to unstable propagation of cracks under conditions of monotonically increasing load. The propagating crack might have its origin in a flaw initially present in the metal, or might arise from a fatigue or corrosion induced crack. The formulation of a rigorous definition of crack stability is a very difficult problem, and for present purposes it will be assumed that a crack is stable if its continued extension requires increasing load in a neutral environment. Materials with high fracture toughness exhibit considerable plastic flow around the tip of an advancing crack. This plastic zone increases in size with crack extension, occupies a substantial part of the thickness, and extends well ahead of the crack. It is the increasing energy demand of this plastic region which keeps the crack stable and requires significant increases in load for continued crack propagation. Structural failures in materials exhibiting this behavior generally show evidence of gross yielding, and cracks may be self-arresting such as is sometimes observed in the fracture of pressurized tanks. These are typical ductile failures. In contrast, materials with low fracture toughness exhibit crack tip plastic zones which are very small compared with the crack length and thickness of the part containing the crack. These materials show little crack extension under rising load and an abrupt onset of unstable crack propagation. The unstable crack then runs at high speeds feeding on the stored elastic energy in the part. Structural failures in such materials are usually catastrophic with much shattering and may occur at loads well below the conventional tensile yield strength. These are typical brittle failures.

The theory of brittle failure has developed to the point where it is possible to design laboratory tests which provide a quantitative measure of fracture toughness under conditions where linear elastic mechanics can be applied (refs. 1 to 4). This field of structural mechanics is commonly known as linear elastic fracture mechanics, and the index of fracture toughness is designated as plane strain fracture toughness (K_{IC}). If a material is sufficiently brittle, in theory it would be possible to establish the design loads on the basis of linear elastic fracture mechanics analysis and the material property K_{IC} . However, in most cases it is impossible to fix the crack size with a high degree of certainty, and under such conditions elastic fracture mechanics can only provide an estimate of load carrying ability, the usefulness of which will depend on the accuracy of the assumptions concerning crack sizes. Plane strain fracture toughness values are a valuable guide in material selection for critical applications and in certain circumstances can be used as an aid in the design of proof tests. Unfortunately linear elastic fracture mechanics has been applied in situations where the crack tip deformations are far too high to permit useful accuracy in the analysis. There is a definite need for objective education in this respect. The

development of elastic-plastic fracture mechanics is necessary to provide quantitative information concerning the behavior of cracks in tough materials. Research is progressing slowly in this area because the work is difficult both conceptually and mathematically. At the present time there is little advantage in attempting to increase this effort which is largely at the stage of exploring various models of the plastic zone development around cracks. In the meantime it appears possible to use cracked specimens in suitable laboratory tests as an aid in the design of proof tests. However, this approach has not been developed to the point where rules for its application can be written.

Selection of Materials

Many different methods have been used to evaluate the fracture toughness of materials. Many are highly specialized tests that have been developed for particular applications and might be called "model tests" in that they attempt to incorporate the major embrittling features of the service environments. Noteworthy are the low temperature impact tests developed by NRL for the selection of steels for ship hull construction. ASTM Standards exist for two of the most popular of these tests, the Nil Ductility Transition Temperature (NDT, ref. 5) and the Drop Weight Tear Test (DWTT, ref. 6). The aircraft industry makes extensive use of model tests, and some become quite complicated in their approach to the actual application. All such tests suffer from their very specialization in that they are useful only in a restricted set of circumstances. Much simpler "screening tests," such as the Charpy V impact or mild notch bar tension test, are frequently used by the alloy producer as indicators of relative embrittlement. These tests have the advantage of small size and easy performance; the disadvantage is that the quantity being measured is difficult to interpret in terms of the material fracture characteristics under the influence of cracks.

More recently, attempts have been made to develop screening tests which are more realistic in that they make use of the substantial knowledge developed over the past 10 years on the fracture behavior of high strength materials. The ASTM E-24 Committee on the Fracture Testing of Metals has issued Methods of Test for determination of plane strain fracture toughness, K_{Ic} (ref. 4), and for sharp notch tension testing of high strength sheet materials (ref. 7). As mentioned previously, the former test method provides a quantitative measurement of the resistance to crack propagation under static load but is restricted in application to relatively brittle materials and requires rather sophisticated instrumentation and analysis procedures. The latter test method was designed primarily for sheet materials (up to 1/4 in. thick) and is restricted in application to materials having yield strength to density ratios above 700000 psi/lb in.⁻³ (about 200 ksi in steel). At the present time we are attempting to revise E338 in such a way that its applicability will be extended to materials of lower strength and larger section size. In making this revision we are working in close contact with representatives of the SAE-AMS groups, who have direct need for such tests. In addition, E-24 is planning to write recommended practices for the testing of surface flawed specimens of a type which has been widely used in the aerospace industry for material selection.

It is important to remember that all these screening tests represent various degrees of compromise and that no one test will serve all purposes. The main object is

to develop as small a number of tests as is needed to do the jobs at hand and to characterize carefully the tests so that their results will not be ambiguous or subject to variations in test technique of data analysis. This, then, is a matter for standardization, and the need for this standardization is well recognized by all who are associated with ASTM E-24, AIA, and the SAE-AMS groups. The necessary research is underway at NASA laboratories and at several industrial organizations.

Data for Hardware Design

In order to establish minimum design properties on a sound statistical basis, it is first necessary to standardize test procedures. This has been done in the case of the fracture property defined in ASTM E-399-70T (ref. 4) as plane strain fracture toughness (K_{IC}). However, this Method of Test has not been in existence long enough to generate a body of data sufficiently large to permit meaningful statistical analysis. Furthermore, the Method of Test is in a tentative status and will likely undergo modification within the next 2 years before becoming a full Standard. At the present time plane strain fracture toughness data (K_{IC}) conforming to ASTM E-399-70T is being put into MIL-Hdbk-5 for information only. When sufficient "good" data have been generated, presumably minimum values of K_{IC} will be listed along with other design mechanical properties. Certainly some index of fracture resistance, measured using a cracked specimen, should be more meaningful to the designer than the tensile elongation or reduction in area values, which now appear in the design mechanical property listings. In most cases these measures of "ductility" have little to do with the performance of the material in any practical structure.

Material Specifications

The SAE-AMS specifications for high strength steels and titanium alloys often contain a statement to the effect that a fracture toughness test should be conducted, but leave the type of test and interpretation of the result as a matter to be established by agreement between the purchaser and the vendor. However, it is the intention of the SAE-AMS group to suggest suitable fracture tests based on ASTM Methods as these become available. The SAE-AMS specifications are very comprehensive and widely used in the aerospace industry; however, individual companies and government agencies have their own specifications. These are in enormous volume and not well known to me. The Air Force has begun to ask for certain minimum values of plane strain fracture toughness (K_{IC}) in the material specifications for high performance aircraft. The increasing attention given to fracture properties by specification writers is basically very desirable. However, in some cases there has been a tendency to emphasize the measurement of plane strain fracture toughness when in fact that property cannot be measured for the section sizes of interest, and is therefore of unknown practical significance in determining structural performance. In fact, for most alloys the specification of a minimum value of K_{IC} is premature because as yet there is insufficient valid data to establish a sound statistical basis for such specifications.

Design Methods

Linear elastic fracture mechanics and its associated plane strain fracture toughness (K_{IC}) values can provide a valuable tool for the designer in his fracture control and proof testing programs, but only when the crack in the structure is limited to conditions of small scale yielding and plane strain constraint. These circumstances are encountered in the fracture of sufficiently heavy sections of structural materials. However, there is an increasing tendency to apply linear elastic fracture mechanics to situations where the basic assumptions of the theory are not even remotely approached because of extensive plastic flow near the crack tip. It is sometimes argued that, even though these assumptions are grossly violated, the toughness values measured and the conclusions reached about structural integrity are "conservative." But experience shows that what may be conservative in one situation may be overly optimistic in another. Unfortunately the fracture behavior of metallic materials outside the linear elastic range of nominal loading is poorly understood and is influenced by many factors that are not taken into account in elastic fracture theories. These factors do sometimes compensate for one another in such a way that on the basis of limited experience one may be led to believe that elastic fracture mechanics can be extended well into the plastic range. Such extension is, at best, unwise and in some cases may be dangerous because at the present time there is no way of predicting the direction or the magnitude of the errors involved.

At the present time it would be well to avoid the involvement of linear elastic fracture mechanics concepts in design criteria except in those cases where there is ample evidence to support the inherent assumptions that fracture will be controlled by small scale yielding and plane strain conditions.

Conclusions and Recommendations

Deficiencies in the Technology: From the standpoint of material selection and component design, the following deficiencies can be recognized in the technology:

1. Experience that has developed over the last 2 years indicates that certain modifications are necessary to the existing ASTM E-24 Tentative Method of Test for Plane Strain (K_{IC}) Fracture Toughness of Metallic Materials (E399-70T).
2. For many materials of current interest, sufficient information on fracture behavior has not been developed using the standard test methods now available.
3. Suitable standardized screening tests are not available for the selection of materials on the basis of their mixed mode fracture characteristics.
4. An elastic-plastic fracture mechanics has not been developed which would permit the "quantitative" measurement of a fracture index outside the range of application of linear elastic fracture mechanics.

5. The relation between fracture properties and conventional strength properties is poorly understood.
6. The relation between metallurgical structure (e.g., distribution and types of nonmetallic inclusions) is not known for major high strength alloys systems.
7. Standard methods for the evaluation of the fracture behavior of extremely brittle materials, such as ceramics and intermetallics, are not available.
8. There is very little experimental evidence relating the behavior of cracks in components with double curvature (e.g., spherical vessels) as compared with the behavior of cracks in flat plates.
9. Empirical methods are available which would permit the design of proof tests where linear elastic fracture mechanics cannot be applied.

Recommended actions: The following recommended actions should be of immediate help to the alloy producer and designer. These actions do not relate to items 4, 7, and 8 above because remedies to those deficiencies are subjects for long-range research which certainly should be supported.

1. Modifications to E399-70T should result from an in-house program now underway at NASA-Lewis. However, additional work concerning the size effects in fracture should be encouraged.
2. The qualification of screening tests now under development at NASA-Lewis will require the establishment of cooperative test programs. These programs should receive adequate support, perhaps through NASA or Air Force contract activities.
3. The development of a background of fracture data will require the establishment of long-range plans on the part of NASA and the Air Force for continuous support of this type of work. In the past such support has been inadequate and sporadic.
4. The ASTM now has a Task Group under Committee E-24 charged with development of fracture tests for very brittle materials including beryllium. The necessary research programs have been outlined, but no funds are available for them.
5. An experimental program should be initiated that would permit the behavior of cracks in spherical vessels to be compared with cracks in flat panels. This should include a range of materials with widely differing toughnesses and tensile strengths.
6. The general procedure for design of proof tests outside the limits of elastic fracture mechanics seems fairly straightforward. What is needed is an experimental program which would explore the limitations of such a procedure.

7. There is an increasing tendency to include K_{IC} values in material specifications and to incorporate linear elastic fracture mechanics into hardware design. These actions are desirable only under a rather restricted set of circumstances and should be preceded by a careful study of the problem by experts who can advise whether the specifications or design requirements are feasible on the basis of present day knowledge.

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STRESS CORROSION

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Background

Stress corrosion in the sense used here refers to the localized attack of an aggressive environment on a metallic alloy in the presence of external loads or internal stresses. Stress corrosion can initiate cracks which can be propagated by fatigue loads or by static loads. If the aggressive environment is coupled with the presence of cracks or crack-like flaws, delayed failure under static loads may be encountered. In some cases the load below which no crack propagation is observed, even for very long exposure times, is only a small fraction of the material's yield strength.

Until recently stress corrosion tests were carried out on smooth specimens. The results from such tests are difficult to use in establishing safe design loads but can be helpful to the designer in selection of materials or to the metallurgist in development of protective coatings (ref. 1). However, smooth specimen test results in some cases may not reveal the susceptibility to delayed failure in the presence of cracks, and for this reason stress corrosion tests using cracked specimens have assumed increasing importance in the aerospace industry (ref. 2). If the appropriate specimen sizes and testing conditions are used, elastic fracture mechanics may be applied and the results expressed in terms of stress intensity factors. This expression has the advantage of achieving generality in terms of crack size and applied stress. Under these circumstances, the test results are useful to the designer in providing an indication of the load levels below which cracks will propagate very slowly or not at all.

Selection of Materials

Stress corrosion tests on smooth and cracked specimens provide the designer with valuable tools for material selection provided that the service environment can be suitably simulated in the laboratory. However, the testing methods as yet are very imprecise and lack standardization. For example, bent or stretched smooth samples are placed on the roof of an industrial building or near the sea and examined periodically to detect the presence of cracks or complete failure. No standards exist for this examination procedure, and, as might be expected from the normal variations in the environment and in the crack detection procedure, a very large scatter characterizes the results of smooth stress corrosion tests. However, with enough information it is possible to make a judgement concerning the relative susceptibility of candidate materials to stress corrosion cracking in a given environment. The degree of confidence in such a judgement increases with the amount of long-time data available, but these data are frequently missing because those requiring the information do not want to wait so long. Unfortunately there is no reliable way of extrapolating such information, nor is such a way likely to be found in the near future.

The specimens used in the delayed failure studies generally contain fatigue cracks, and, as mentioned previously, the results can sometimes be usefully presented in terms

of stress intensity factors. However, it should be realized that this method of data presentation is helpful in generalizing the results only if the test conditions meet the requirements of a plane strain fracture toughness test, and they seldom do. Many different specimen geometries (specimen sizes and crack lengths) are in use, and, unless the proper conditions for elastic crack stress analysis are met, there is no way of comparing the results from tests on different geometries. Standardization is badly needed here and is being undertaken by Committee G-1 of ASTM with the help and advice of the members of E-24.

Compilations of stress corrosion data are badly needed. The DMIC Reviews and the Aerospace Structural Metals Handbook contain some but not nearly enough of this type of information. To be useful to the designer, stress corrosion data must be carefully selected and digested by specialists in the field and correlated with other data, such as the static fracture properties.

Data for Hardware Design

From the foregoing discussion it is evident that stress corrosion test data as available today will seldom be of use in setting allowable design loads. Under circumstances where the crack sizes are known and where linear elastic fracture mechanics is applicable, it may be possible to obtain an upper limit of the stress intensity factor below which delayed failure in a corrosive environment would not occur in the expected lifetime of the structure. However, the presence of cyclic loads can greatly complicate the problem, and meaningful data can be obtained only if the laboratory test closely simulates the major features of the service loading conditions and environment.

Material Specifications and Design Methods

Requirements for stress corrosion tests using smooth specimens appear in some SAE-AMS documents. In such cases the type of specimen, stress level, and means of exposure are specified. The requirement is then stated that no evidence of stress corrosion shall be evident following a prescribed exposure time. Individual companies have their own specifications concerning the stress corrosion resistance of metallic materials, and these vary widely in type and scope. The lack of standardization greatly hampers one who attempts to relate one specification to another.

There are no design methods specifically related to stress corrosion. This problem is complicated by the effects of fabrication variables which can introduce residual stresses. As explained in the section Data for Hardware Design, in some instances it may be possible to derive an upper limit on the stress intensity factor which can be applied without experiencing delayed failure in the presence of cracks and aggressive environments. However, the designer generally handles the stress corrosion problem by material selection and, where possible, by providing protective coatings.

Conclusions and Recommendations

Deficiencies in the technology: From the standpoint of material selection and design, the following deficiencies can be recognized in the technology:

1. Improvements in the precision of crack measurement would be desirable for the presently used stress corrosion tests that employ smooth specimens.
2. Standardization is badly needed for stress corrosion tests which employ cracked specimens. Without such standardization the test results have no general usefulness in either material selection or design.
3. Compilations of stress corrosion data prepared by experts and presented in their most readily usable form are badly needed.

Recommended actions: The following actions are recommended as being of help to both the alloy producer and the designer:

1. Stress corrosion tests using both smooth and cracked specimens should be conducted on any new combination of structural material and environment. It is not proposed that all conceivable variations of the new environment be investigated but rather that the extremes be explored. For example, if sodium chloride aqueous solutions are involved, the extremes in expected concentrations should be investigated. There is sufficient technical knowledge available today to specify the types of specimens required to characterize an environment as either non-aggressive or potentially dangerous. There is, however, no generally recognized way of quantifying the risk without extensive tests tailored to the particular application.
2. Standardization activity for cracked stress corrosion tests is already underway within the ASTM Committee structure. The development of suitable test methods will require experimental programs that are designed to establish the influence of specimen dimensional variables. These programs will need support.
3. The DMIC and the Aerospace Structural Metals Handbook should be encouraged to emphasize stress corrosion information and to attempt to relate the susceptibility of stress corrosion to other mechanical properties, such as the strength level of the alloy.
4. Consideration should be given to establishing a "Data Center for Corrosion" that would employ the services of experts in making an analysis and presentation of the voluminous amount of data now being generated, including data already in existence in the literature. Such an activity will ultimately be necessary because the present sources providing compilations will run out of capacity.
5. Following the establishment of standard test methods, continuous data generating programs should be established that would feed data to those making the compilations.

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HYDROGEN EMBRITTLEMENT

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Background

Hydrogen can be a bad actor when introduced into many metals because it can greatly reduce their load-carrying capacity. In classical hydrogen embrittlement, hydrogen is in solid solution and is introduced by electrolytic charging processes, acid pickling, or by corrosion reactions. Hydrogen introduced in these ways can cause delayed failure under static load in many high strength alloys, and the embrittling effect observed increases with an increase in the severity of the stress concentration (ref. 1). The presence of gaseous hydrogen can reduce the load-carrying capacity by increasing the rate of crack propagation in static and cyclic loading for certain titanium and nickel base alloys, as well as in nearly all high strength steels (ref. 2). The magnitude of the embrittlement depends on the temperature and pressure, with substantial effects being observed at ambient laboratory conditions for high strength steels. Recent tests by Boeing show that a large embrittlement of the nickel base alloy Inco 718 occurs at 70°F when cracked specimens are subjected to sustained load in 1400 psi hydrogen (ref. 3).

If high temperature and high pressure are present simultaneously, the hydrogen may react with elements in the metal to produce a general disintegration. This phenomenon is more properly called hydrogen attack and in steels is the result of reaction between hydrogen and carbon to produce methane which collects at the grain boundaries. Pressure buildup at these points can cause blistering and general internal destruction of the metal.

There is an enormous volume of literature relating to classical hydrogen embrittlement, and ways have been developed for controlling the plating and pickling processes for commonly used alloys so that the risk of hydrogen embrittlement should be very small (ref. 1). However, tests for susceptibility to this type of hydrogen embrittlement have not been standardized. This makes judging the relative sensitivity of different alloys difficult unless a broad background of practical experience exists. At present ASTM is attempting to develop the necessary test methods that will permit such standardization. Consideration is being given to both machine notched and fatigue cracked specimens.

Various tests have been proposed for sorting materials regarding their susceptibility to gaseous hydrogen embrittlement, but the field is so new that no standardization activities have been started. Test methods using smooth specimens have been developed by Rocketdyne under NASA contract and have proved very useful in investigations of the effect of high pressure (10 000 psi) hydrogen. Research programs using cracked specimens subjected to high pressure hydrogen are underway at Gulf Research and U.S. Steel Company, but the data are apparently not available to the public. One method that holds promise for overcoming the deleterious effect of high pressure hydrogen in gas storage vessels is the introduction of a liner (e.g., aluminum) which in itself is not affected by the hydrogen. Hydrogen gas which diffuses through the liner

could then be vented to the atmosphere by a suitable system of narrow grooves cut into the inner wall of the vessel. This procedure is feasible during vessel fabrication, but probably not practical for vessels that are already in use. In such cases, the gas pressure should be reduced to the lowest value consistent with the flow requirements, and the vessels should be subjected to as few pressure cycles as possible. The problem of avoiding hydrogen attack is largely one of alloy selection although design tricks such as the use of liners may be of value in certain cases.

A very serious problem may be encountered if high strength steels, titanium alloys, or nickel base alloys are used without protection in critical parts subjected to hydrogen gas. The effects of temperature, gas pressure, and load rate need to be investigated for candidate alloys considered for any proposed hydrogen fueled engine.

The data outlining the susceptibility of various materials to hydrogen embrittlement through electric charging is adequately documented both in DMIC and in the Aerospace Structural Metals Handbook. The effects of gaseous hydrogen are poorly defined at present but the available data are well documented by DMIC.

Conclusions and Recommendations

As previously discussed, the possibility of failure by classical hydrogen embrittlement can generally be eliminated through proper selection of materials and fabrication procedures. There is little excuse for problems arising from the introduction of hydrogen by electrolytic charging because the means for avoiding this are well known. However, occasionally a service part will fail because of this type of hydrogen embrittlement, and the question then arises as to what can be done to avoid failure in similar parts which may also contain hydrogen. In such cases the suspected hardware should be removed from service and subjected to a suitable baking treatment, and when necessary this should be preceded by stripping off the plating.

The protection of storage vessels from embrittlement caused by high pressure hydrogen at ambient temperatures is possible by the use of liners which should be incorporated in all new designs. Vessels which cannot be lined should be operated at reduced pressure. Unfortunately the degree of stress reduction is not easy to specify and will depend on the material. Experts should be consulted in each case.

The problem of gaseous hydrogen embrittlement thus far has been of major concern to the aerospace industry only in ground storage vessels for high pressure hydrogen. However, hydrogen fueled jet engines might be in serious trouble if critical parts were subjected to gaseous hydrogen. A great deal more information is needed to define the simultaneous effects of pressure, temperature, and load rate on the embrittlement of candidate alloys for such applications.

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OXIDATION

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Background

For the purpose of this discussion, oxidation is defined as the chemical reaction of a material with oxygen at elevated temperatures. Propulsion systems, primarily turbine engines, are currently the most important application of structural materials at elevated temperatures. In the future, the space shuttle will represent another significant application.

Oxidation per se has not been a frequently observed failure mode for "high strength structural materials" because such materials, in the usual connotation of the phrase (e.g., steels), have adequate oxidation resistance in the temperature regime where their high strength is utilized. However, when we combine high strength with high temperatures and speak of high-temperature, high-strength structural materials, oxidation does become important. Materials in this category would include superalloys, refractory metals, and dispersion strengthened alloys that retain their usable strength to temperatures so high that their oxidation resistance is wanting. Even in these cases, oxidation per se may not be the failure mode, but the accelerating effect that oxidation might have on other failure modes, such as thermal fatigue and stress rupture, is of concern. The following remarks are then directed at these high-temperature, high-strength structural materials.

There are many features of gas-metal reactions which are not fully understood, particularly from a mechanistic point of view. On the other hand, many facets of oxidation are sufficiently well understood so that, given the proper evaluation tests, useful design data could be generated. Since oxidation has not been a truly life-limiting design factor in the past, there has been little effort to obtain design-type data. Thus the question arises as to how much understanding is required in order to allow the generation of design data. For the purpose of designing a stressed high temperature structural component, the designer would be interested in two questions: (1) is the oxidation resistance of the material sufficient so that it will survive at temperature for the expected life time, and (2) during this expected lifetime, will the effects of oxidation have degraded the mechanical behavior of the component and to what degree? These questions can be answered by conducting the proper tests. Such tests can be devised and conducted today. However, there is not sufficient basic knowledge to allow the number and type of such tests to be truly minimized; instead tests must be run that simulate the hardware environment as closely as possible.

Selection of Materials

A designer would be hard pressed to find good comparative data in the literature of today to make an intelligent selection of materials on the basis of their oxidation resistance. He could find general information that would distinguish among types of

alloys, for example, nickel base or cobalt base, high chromium level or low chromium, but he could not select an alloy from handbook data. This situation is not caused by the lack of adequate test methods, but rather it arises from the difficulties of defining and standardizing tests of general value. These difficulties arise because the oxidation behavior of an alloy is strongly dependent on environmental factors that may be peculiar to a given application. For example, consider the two problems of selecting alloys (1) for the heat shield of a reentry vehicle, and (2) for the stator vanes of a gas turbine engine. In the reentry use, oxidation behavior at reduced pressures and under dynamic heating is very important. However, for the engine application, the alloy behavior at high pressure in combustion products under conditions of severe cycling is paramount. Alloy behavior can be drastically different in these two cases. Thus, it is impossible for one test to allow the selection of alloys for these two applications.

The most prevalent form of oxidation data in the literature gives the change in weight per unit area of a small sample as a function of time at a set temperature. Such data are virtually useless for the selection of an alloy for a given application for the following reasons:

- (1) The data give no insight into the absolute amount of metal consumed by the oxidation process and the resultant loss of load-carrying ability. Only a few investigations of the oxidation behavior of materials attempt to correlate weight change with base metal loss or changes in microstructure.
- (2) The data give no insight into the loss of load carrying ability due to internal oxidation and changes in alloy composition.
- (3) The recorded weight changes (usually weight gains) can be affected in an unknown manner by vaporization and spalling of scales that cause weight losses.
- (4) The data are usually for short times—far short of the intended life of a real component.
- (5) The data are usually isothermal without the more realistic temperature excursion a real component would experience.
- (6) Little information is usually given regarding the surface preparation of the samples—a factor that can have profound effects on measured weight changes. If such information is given, the surface preparation is usually unreal for component hardware.

More useful information would be the overall change in specimen thickness and remaining thickness of the unaltered alloy for long times in both the isothermal and cyclic temperature conditions, with and without stress. Such data would be of greatest utility if obtained in air at 1 atmosphere over a range of times, temperatures, and stresses that cover the useful life of the alloy. The same information should be gathered for coated alloys. All the preceding should be augmented by studies of microstructural changes and identification of oxidation products, including their morphology, and their total emissivity.

The preceding information would allow comparison of alloys and their relative ability to withstand a high temperature air environment. In addition, the designer would want to know how this high temperature exposure has affected the mechanical behavior of the candidate alloys. Here, any change in mechanical properties (strength, creep, ductility) would be noted.

The type of information discussed here is not available except partially in isolated cases of individual alloys. Realistic comparisons of alloy behavior are difficult if not impossible. In order to provide the necessary spectrum of data a great deal of standardization of test parameters is required. For example, all alloys should be evaluated in the same sample geometry following identical and realistic surface preparations. For cyclic testing, the cycle frequency and severity (both up-shock and down-shock) would have to be defined. A singular and consistent technique for measuring remaining metal thicknesses is required.

Relevant to this discussion is a current attempt by the Defense Metals Information Center to compile a Handbook of Basic Data on Hot Corrosion and Oxidation. Such a compilation will be useful inasmuch as it will serve as a ready reference for all available data. However, its utility in selecting alloys for applications will be severely limited by the lack of standardization that will be apparent in the compiled data.

Hardware Design

Data relevant to hardware design is nonexistent in the field of oxidation. Many points relevant to this subject were discussed previously.

The use of statistical data to predict expected minimums has been applied to life prediction for coated coupons. However, again as previously, the value of these data is probably limited when applied to a materials selection situation because of non-standardized testing and evaluation techniques.

Materials Specifications

An oxidation performance criterion is not contained in the specification of alloys. An alloy that is particularly good in oxidation may be compared with other alloys in the vendor's literature; however, such comparisons are usually too far removed from real applications to be useful. A typical vendor brochure might show his new "alloy A" to have only one-tenth the weight gain of "brand X alloy" after 100 hours at 1800°F. For a designer to select alloy A based on this information for a cyclic operation in a high velocity gas could indeed be a costly mistake.

Sometimes in development programs seeking, for example, a higher strength alloy, the sponsor will require that the new alloy have oxidation resistance equal to or exceeding an existing alloy under a certain set of conditions. This approach is fine for setting a target for this particular program, but it does little to encourage the generation of data that could eventually be used to compare many alloys.

Conclusions and Recommendations

Deficiencies in the technology: The technology for application of structural materials in high temperature oxidizing environments is not adequate. The designer is frequently unaware of profound changes in the mechanical properties which can result from exposure of nominally oxidation resistant material systems to oxidizing environments. This deficiency arises in part from a lack of sufficient information concerning the alteration

of mechanical properties by oxidation processes and from documentation inadequacies related to the current fund of knowledge. A great deal of published data relate to weight gain as a function of exposure temperature and time under steady state conditions. Such data are not useful to the designer who needs an indication of the degradation of load-carrying capacity that can be expected, and who is often faced with a variable temperature and load history in the actual structure. The materials engineer is hampered in the job of estimating service performance from laboratory data by poor documentation of test results in technical reports. Thus, material chemistry, details of sample preparation, test environment, and residual microstructure are often poorly defined.

Recommended actions: There are two areas where additional experimental data are badly needed to overcome the present deficiencies in the technology base:

1. The change in the load-carrying capacity (residual strength) and thickness of undamaged material should be determined as a function of temperature and time of exposure to the oxidizing atmosphere. Such data should include the effect of cyclic temperatures.
2. Velocity and pressure have an effect on the oxidation process, and for this reason service simulating test data may be required in some cases. Examples would include the nozzle vanes of turbojet engines that operate in high velocity and high pressure oxidizing gas streams and the skin of reentry vehicles that operate in air at high velocity but low pressure.

SUBCRITICAL FLAW GROWTH

by Herbert F. Hardrath
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Background

As indicated under the section "Cycle Dependent Fatigue," many efficient structures are constructed with damage tolerant features to reduce the likelihood of catastrophic service failures. In damage tolerant designs, the high likelihood of significant flaws or other damage is recognized and accepted. Materials are selected, design stress levels are adjusted and the structural details are configured to inhibit crack growth. During service, systematic nondestructive inspections are performed to identify cracks and corrective maintenance measures are taken to restore or improve structural strength.

Three major pieces of information are required to assure that damage tolerance has been achieved.

1. All significant flaws must be identified, whether they were introduced during manufacture or were developed in service by fatigue, corrosion or inadvertent damage. In military vehicles, battle damage might also be a concern. Adequate NDI procedures must be employed. This technology is discussed elsewhere in this report.
2. The rate at which the crack will propagate under service conditions must be estimated. These estimates form the basis for setting inspection intervals and replacement schedules such that cracks do not cause catastrophic failure.
3. The progressive reduction in residual static strength must be evaluated quantitatively to assess the likelihood of fracture under service conditions.

Another section of this appendix treats the technology on Fracture.

The remainder of this section is devoted to subcritical flaw growth.

Selection of Materials

The rate at which a crack grows in a given material is usually associated with the linear elastic stress intensity factor K for the configuration and applied stress. Under cyclic loadings the range in the stress intensity factor ΔK must exceed some threshold value for the crack to propagate. For constant amplitude loadings, the mean value of the factor K has a significant effect on the rate of growth. Paradoxically, several recent investigations have shown that cracks grow more slowly under high gross stress levels than are expected on the basis of linear elastic analyses. Simple power laws have been proposed to correlate limited collections of data, but they cannot account for many effects, such as the increasing rate observed as the crack length approaches its critical value.

Although considerable research has been devoted to the study of fatigue crack propagation, standard methods of evaluating the phenomenon have not been adopted and no systematic catalog of properties is as yet available. Generally, the contractor for a given vehicle is forced to generate empirical data for the materials of interest to him.

Design Procedures

Service loadings are seldom limited to constant amplitude loadings. Thus, crack growth under complex time histories must be accounted for. Many tests have shown that nonlinear interaction effects are introduced, particularly following occasional high loadings. Recent studies have led to empirical relations to predict these effects and to a detailed study of "crack closure" even when the cracked part is under tensile load. However, these procedures are too new to be adopted as design rules. Thus, a considerable number of ad hoc tests are usually required to observe crack growth under simulated service loadings. Fortunately, most of the effects noted are in the direction of providing longer lives than are estimated by linear methods.

The service environment frequently includes hostile corrodents to varying degrees. Two effects are noted: First, the rate of fatigue crack propagation is usually increased, especially if extended time is available for corrosive action to operate. Second, the crack may grow due to corrosion under prolonged steady stress. The steady stress may arise from residual stresses introduced during manufacture, from the dead weight of the structure when not in use or from the "1-g" flight condition. Research on this phenomenon has identified a threshold stress intensity level K_{th} which must be exceeded to produce crack growth, but rates of growth cannot yet be estimated. Some materials suffer enough crack growth to cause failure in minutes under moderate stresses and a water environment.

Similarly, a service environment that involves significant temperature variations may produce still another influence on rates of crack growth. Complex interactions arise between changes of properties due to heating, intensification of corrosive influences and local creep effects which tend to make the phenomenon sensitive to time at load or temperature. Effects due to temperature variations can accelerate crack growth by factors of 100.

A further parameter in the estimation of rates of crack growth is the influence of structural configuration. Mathematical analyses have been developed for the stress intensity at cracks emanating from simple stress concentrations like holes, and some experimental verifications have been performed. However, a host of possible geometrical configurations, combinations of stress states and shapes of cracks pose a formidable challenge to researchers in this area. Similarly, the effects of stringers have been analyzed and experimentally verified. Rates of crack propagation can be reduced by factors greater than 10 by judicious deployment of stiffeners. Thus, research in this area should lead to significant improvements in life and residual strength.

Conclusions:

The foregoing discussion reveals that the use of crack propagation as a design tool is still in its infancy. Research in the area has accelerated rapidly during the past decade. This work has led to an appreciation of the parameters involved and some approximate rules of thumb. However, a large number of parameters influence the phenomenon and most of them have not been investigated to the extent necessary to provide quantitative design rules. Catalogs of properties and analytical procedures are needed.

Recommendations:

1. NASA should sponsor a program of gathering the existing data on subcritical flaw growth, fitting rational analytical expressions to the data and compiling the results in a format useful to the designer. Data-generating studies should be sponsored to develop consistent test methods and to fill existing data gaps.
2. A systematic investigation of the influence of other important parameters should be planned and executed. Special emphasis should be placed on interaction effects for complex time histories of stress, on the effects of practical structural configurations, and on time-dependent effects at elevated temperatures.

NONDESTRUCTIVE EVALUATION

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Background

Adequate nondestructive evaluation, like the escape system on Apollo, is not a substitute for high quality manufacture, but rather a final safety factor. Regardless of the limitations of the various NDE systems, they are still the final recourse in the prevention of structural failure. These limitations must be understood by the designer, manufacturer, and inspector if maximum use is to be made of advanced structural materials. Aside from the technical limitations of the systems, there is an equally important management problem—assuring that the latest NDE technology information is made available to the tester, is included in appropriate specifications, and is used conscientiously in inspection.

As the use of high strength materials is increased, while attempting to maintain low safety factors, dependence on NDE capability increases. In general, as the strength level of a material increases, it becomes susceptible to ever smaller flaws, and the ability to detect these defects must increase proportionally. The alternatives to improving the technology are to avoid use of the stronger materials, use them at a degraded stress level, or limit their use to applications where comprehensive load testing is feasible.

NASA efforts in development of improved NDE techniques are largely concentrated at Marshall Space Flight Center. Lewis Research Center has a small program and is initiating more work. Current work at Marshall Space Flight Center has been largely stimulated by fabrication problems, mostly welding and bonding. The S-IV B-503 test stand explosion (Jan. 1967) instigated development of an eddy current test to check weld wire on titanium pressure vessels. Other NDE improvements, cited in response to the S-IV B-503 Review Board's recommendations concerning inspection technique improvement (ref. 1), included development of the more sensitive Ultrasonic Delta technique. This technique has been applied to factory testing of current production steel forgings for the wing pivots and carry-through structure on the F-111 airplane (ref. 2). Other areas of current interest include radiographic image enhancement and readout methods and techniques for measuring stress, stress corrosion, and an assessment of filamentary composites. Investigations are underway to allow detection of metallurgical defects such as grain boundaries, improper alloys, etc.

Capability of Crack Detection

The need for a comprehensive evaluation of NDE procedures was a conclusion in the assessment of the hydrotest failure of the 260-inch SL-1 motor case (ref. 3). Unfortunately the majority of NDE equipment was developed using instrument calibration standards which were far from representative of cracks in actual hardware. Thus, in

most cases the resolving power of a given method in terms of crack size is frequently much poorer than would be indicated by its specifications. It is only very recently that attempts have been made to use actual cracks in the development and the calibration of NDE techniques. These studies have revealed that the full potential of NDE to assess a structure requires the application of several complementary techniques (e.g., radiography, ultrasonics, and liquid penetrants) to that particular structure. The state of the art of NDE for structural composites is considerably less mature than that for homogeneous metallic structures. The procedures for evaluating composites are largely adaptations of those for metals, and it is only recently that new approaches have been considered. Among those being evaluated by DOD and NASA are systems employing microwaves, thermal characteristics, holography, and neutron radiography. More efforts are needed in this area, particularly if the NASA shuttle is to employ lightweight nonmetallic structures.

It is important to recognize that dangerous flaws can sometimes be present in the form of structures which are essentially coherent with the matrix (e.g., grain boundary films, hydrogen embrittled regions, etc.) and, therefore, impossible to detect by any presently available NDE technique. These types of structures are more likely to be encountered in complex high strength alloys than in the more commonly used materials. Their development is influenced by fabrication processes and heat treatment, and they can be revealed by metallurgical examination and destructive testing. It is important that the tendency of a new material to form such structures be investigated before it is placed in service.

No NDE procedure can be effective if the structure is so designed that "inspectability" is compromised by inaccessibility of the critical areas to the inspection equipment. Thus the inspectability of the final hardware must be a criterion in the selection of materials and in the assignment of safe operating stresses. In the area of materials, it is possible that a reliable, flaw-tolerant, conventional material may be superior in weight and cost to an advanced ultra-high-strength material which may require large safety factors because of NDE uncertainty. All major programs should have an overall NDE plan, assembling inspection criteria and procedures in a document addressed to the operator. Geometrically similar models of the hardware to be tested should be made available for flaw detection equipment checkout. Quality engineers trained in NDE should review fabrication documents to ensure that critical flaws can be detected by the methods proposed.

Description and Specification of Techniques

The current state of technology in NDE is difficult to establish precisely. It is known by experts and partially understood by users, but it has not been properly documented. Thus, there is no source that describes the qualitative and quantitative capabilities of the various NDE methods as they are known. NASA has published a series of reports (refs. 4 to 16) describing the range of NDE methods and applications as well as a sequence of training manuals (refs. 17 to 21). Published literature and commonly used specifications and standards emphasize the qualitative measures of NDE methods rather than their resolving power in regard to actual cracks. Present

fabrication and hardware specifications usually describe acceptance/rejection criteria based on the theoretical capabilities of inspection methods rather than on the actual performance as derived from test data and/or fracture mechanics analysis. Much NASA-sponsored test data and fracture mechanics analyses are developed for a particular structure and are recorded in contractor-generated technical documents (e.g., test reports or inspection standards). NASA has no specification policy or method of applying such data in a form useful to anyone other than the original contractor. It should be required that quantitative acceptance/rejection criteria be used rather than simply referring to the theoretical capabilities of the systems. It should also be required that the NDE systems used should be validated for the job.

Conclusions and Recommendations

Deficiencies in the technology: The following deficiencies in the present NDE technology can be recognized:

1. It is apparent that the theoretical potential of presently available NDE techniques is frequently not realized when applied to the problem of finding crack-like flaws in actual hardware.
2. No generally recognized standards exist which permit judgement of the actual precision of a particular NDE technique, nor is there any general agreement as to how NDE operators should be qualified.
3. Frequently the potential value of NDE techniques is compromised by a lack of inspectability of the finished hardware.
4. The development of NDE techniques for composite structures is in an embryonic state, and at present our capability is only marginally adequate to satisfy NASA's needs.

Recommended actions: The following actions are recommended to improve the capability of NDE methods and to increase the reliability with which they can be applied to practical hardware items. The alternatives to actions such as these are to avoid using new high strength materials, use them at degraded stress levels, or limit their use to only those structures where comprehensive load testing is feasible.

1. Standards should be developed for the assessment of the sensitivity of various NDE techniques to actual cracks and crack-like flaws.
2. All major hardware programs should have an overall NDE plan that would assemble all pertinent inspection criteria procedures into a document addressed to properly qualified operators. These plans should be developed in the initial phases of design and should take into account the limitations of the available NDE equipment and inspectability of the finished hardware. Inspection steps

should be carefully defined in terms of the fabrication stages, and special consideration should be given to field inspection problems.

3. To record the present state of the art in NDE, it is recommended that a design criteria monograph be issued by NASA that would cover the known qualitative and quantitative limitations of presently available NDE methods. This document should be updated regularly.
4. Special emphasis should be given to the development of NDE methods for composite structures.
5. An organizational focal point should be established within NASA to act as a central coordinating point for NDE activities, be an authoritative reference source, minimize duplication in research and development activities, and help identify those areas needing additional research.

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COMPOSITE MATERIALS

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Status of Technology

Various forms of composites have been in extensive use for many years. However, with the advent of the more recent high strength and high elastic-modulus fibers, it has become possible to develop advanced fiber-matrix systems and fiber composite reinforced metals with unusually high strength and modulus properties. Of even greater importance to the aerospace industry is the fact that high strength and modulus can be obtained at the same time the component or structure weight is reduced because of the high strength-to-weight ratios and high modulus-to-weight ratios of these new materials. The manner in which information is gathered concerning these materials, the manner in which they are tested, designed, and fabricated is quite different from that for conventional metals. Therefore, new methods and procedures are required to assure the integrity and reliability of composite components and structures. For example, one important difference concerns the way in which a component or structure is constructed. In metal fabrication, the alloy is formed first and then cast, worked, or machined into the final form. In composites fabrication, the constituent fibers and matrix are "built up" by one of several methods directly into the final shape or configuration. In other words, "properties" or "characteristics" are built into the component, not only as a function of the properties of the constituents, but also as a function of the way the constituents are placed in the final product. The technology base that must be established to permit the reliable use of components produced in this fashion will necessarily be quite different from the type of technology base used for metals.

The design of advanced composite components or structures is based on methods or procedures that have been evolved relatively recently and are not as sophisticated as would be desired. As a result, composite components are often fabricated in a semi-empirical fashion and then tested as components to determine how to improve their design. The design methods such as the laminate analyses must be improved and expanded to permit design optimization without expensive experimental iteration.

In connection with the topic of developing a technology base, there is a general problem of identification and characterization of composites that must be dealt with. Very frequently, property data are quoted in the literature (even in the handbooks) without identifying the composite beyond giving the fiber and resin names and perhaps the fiber orientation. Such data can be used only as a rough indication of the performance of a general system and cannot be used for design or research purposes. Mechanical and thermal properties can vary widely depending on additional factors such as:

- (1) Amount and direction of fiber in each layer
- (2) Fiber or matrix volume content
- (3) Void content and distribution

- (4) Fiber surface treatment
- (5) Fabrication procedure
- (6) Cure procedure (pressure, temperature, and time)
- (7) Postcure treatment
- (8) Method of testing
- (9) Test environment

The various laboratories and agencies should be encouraged to provide complete identification of a composite when property information is published. Such data can then be used for design purposes (at least material selection), correlation purposes, and research background information.

Selection of Materials

Many standards or handbooks have been published for composites (refs. 1 to 5). An examination of these standards or handbooks indicates considerable disparity among the recommended test specimens and procedures. There are, for example, at least five published methods for making an interlaminar shear test. In one of these tests (the short beam shear test), there is a wide variance in the ratio of span to depth used by different laboratories. In other words, in addition to the variations published in the standards, there are further variations imposed by the people using the tests. Considerable work needs to be done to unify the standards and procedures to eliminate the ambiguity that presently exists. This can be done by an analytical and experimental procedure in each case to determine the most appropriate method for the information desired.

In lieu of established, definitive, and well-accepted procedures, the industry is probably best advised to choose test specimens and methods that most closely represent the conditions encountered in a given design or component. This procedure, however, leads to much redundancy in testing and accumulation of data that are difficult to compare with data from other tests.

Data for Hardware Design

In general, data quoted in the literature are average data and are unsuitable for design purposes. Because of the unhomogeneous nature of composites, the manner in which they are fabricated, and the intrinsic variability of the properties of the constituents, there tends to be more scatter in the data from a given set of tests than might be desired. Statistical data are needed to provide the information required for reliability study purposes and to establish lower bounds. As stated previously, such data must be accompanied by a complete identification of the composite to make the information of value to the designer. In certain cases, statistical data have been generated for specific fiber-matrix systems, but these data are usually retained as company proprietary information.

In particular, data are lacking for temperatures other than room temperature, for directions other than parallel to the fiber, and for most thermal characteristics.

The use of data banks with quick information retrieval would be most helpful for design purposes and should be established along the lines of existing metal alloy systems. The generation of additional property data for data bank storage is highly desirable. One drawback in this proposal is the fact that the rapid progress in developing new fiber-matrix systems causes existing data to become out-dated rather quickly.

Materials Specifications

In general, materials specifications have not been well established or negotiated between the consumer and the supplier. Stated constituent properties are usually quite "loose" with a high degree of variability involved. It generally remains for the consumer to fabricate specimens or components and to establish his own specifications in building a specific piece of hardware.

Design Methods

Composite laminate analyses, and winding and overwrapping analyses exist, but require experimental verification in most cases and also extensions to include all the factors that should be considered in design. In particular, analyses must be developed that will permit the optimization of composite layups to provide the lightest and strongest configuration, and design criteria must be evolved and established for all composite and composite reinforced metal structures.

Special Problems

1. Translation of uniaxial specimen data to structural or component strength values—
The use of data obtained from uniaxial, simple specimens for the design of complex composite components or structures can be very dangerous. Careful allowance must be made for possible reductions in property values in going from the specimen data to component or structure values due to a host of factors including differences in:
 - a. Fiber orientation and distribution
 - b. Fiber content
 - c. Void content
 - d. Fabrication
 - e. Cure procedure
 - f. Environment

It is, therefore, very important in the design of composite structures to use data that are appropriate and commensurate with the configuration and conditions existing in the structure.

2. Effect of residual stresses and thermal cycling on structural integrity—Because of the differences in coefficient of expansion of the fibers and matrices, considerable residual stresses transverse to the fiber direction can occur when the composite is returned to room temperature from the maximum temperature of the cure cycle. This phenomenon occurs in multi-ply composites and, in general, produces higher residual stresses as the angle between the fibers in adjacent plies becomes greater. Cracking of the matrix can occur in cooling to room temperature. Possible degradation of strength properties of the composite should be considered in any design involving this phenomenon.

Degradation of strength properties can also occur as a result of cycling between two temperature levels. This is similar to the low cycle thermal fatigue process in metals. In addition, deterioration can occur with time (particularly in the resin of resin-fiber composites) as a function of the exposure temperature.

3. Failure mechanisms of composites—Considerable information is needed concerning the various failure mechanisms that can occur in composites. In particular, information is required concerning the effect of cracks, flaws, and other stress raisers on structural integrity. Flaw or crack propagation rates are needed as a function of stress levels, number of cycles of loading, and the environment.
4. Effect of lightning strikes on composites—Some high strength fibers are very strong dielectrics and subject to damage by the passage of high electrical currents of magnitude encountered in lightning strikes. Consequently considerable information is needed on the damage effects in various fibers of fiber-resin matrix composites when struck by lightning, and on the protection of these types of structures when used in aircraft or space vehicles.
5. Nondestructive inspection—Many nondestructive testing methods have been examined in great detail to determine their applicability to finding defects, flaws, and cracks in composites that occur in manufacture or in service. Some of the methods, such as ultrasonic mapping, have shown some promise for isolating and defining certain types of defects. However, other types of defects are very difficult to detect, particularly in large parts where the amount of time required becomes excessive.

The situation is complicated further by the fact that there is very little information concerning the propagation rates of flaws and defects under cyclic loading. It is therefore not clear in most composite systems what sizes or numbers of flaws can be tolerated. Preparation of specifications that define limits for flaws and defects at this time is largely guesswork.

Conclusions and Recommendations

The development and application of fiber composites, although progressing rapidly, must be considered to be a new technology in its very early stage of development. Their application as large areas of load-carrying members of large vehicles must await the evolution of this new technology and suitably trained people. With concentrated effort, fiber composites can be applied to critical hardware where the potential weight savings justifies the effort.

As indicated in the more detailed discussion of this topic, however, almost every input required for rational design of highly stressed hardware from composites requires additional information. Typical needs are:

- (1) Standardized test methods to determine mechanical properties
- (2) Properties for material selection and design
- (3) Specifications for the components (matrix and fiber) of the composites
- (4) Improved design methods incorporating the effects of manufacturing residual stresses and thermal stresses, particularly for structures requiring other than uniaxial fibers (design method manuals)
- (5) Nondestructive evaluation methods to ensure the quality of the finished product and its integrity in service

Additional problem areas are:

- (1) Impact, toughness, and fracture
- (2) Lightning protection

References

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2. Composite Materials: Testing and Design. ASTM STP 460.
3. Plastics for Flight Vehicles, Part I: Re-inforced Plastics. MIL-Hdbk-17.
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5. Structural Design Guide for Advanced Composite Applications, Air Force Materials Lab., August 1969.

APPENDIX C: Documentation and Communication of Information

Panel Members:

Chairman, G. C. Deutsch, NASA Headquarters

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APPENDIX C: DOCUMENTATION AND COMMUNICATION OF INFORMATION

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This appendix presents the report of the Panel on Documentation and Communication of Information. The information to be communicated includes failure analyses, mechanical and physical properties of structural materials, the influence of fabrication processes and service conditions on these properties, and methods of structural analysis that incorporate these properties in design procedures. The Panel addressed the question of whether these types of information are adequately documented and communicated throughout NASA's program management system. Consideration is given to the following: (1) sources of information, (2) accessibility of information, and (3) discipline in the use of information. The conclusions and recommendations of the Panel are summarized in the final section of this appendix.

Sources of Information

Many sources of information are available. Among them are:

- (1) Nationally recognized handbooks
 - (a) MIL-Hdbk-5 provides design mechanical properties for metallic alloys and for some structural elements such as spot welds. These properties are in most cases established on a recognized statistical basis and are accepted for the purposes of design by DOD and FAA. In general, only the most commonly used alloys are included in this handbook because a large amount of data is necessary to establish design values with a high degree of confidence. Alloy design values are given only for the strength as determined in tension, compression, shear, and bearing. Typical or average values are sometimes given for elastic moduli, fatigue strength, plane strain fracture toughness, and certain physical properties. This handbook is very limited in its coverage of strength limiting factors such as stress corrosion, hydrogen embrittlement, high stress concentrations, etc.
 - (b) MIL-Hdbk-17 is similar in most respects to MIL-Hdbk-5 except that it is concerned primarily with the mechanical properties of glass-reinforced plastics and to a lesser extent with boron-reinforced plastic; it does not present design formulas.
 - (c) MIL-Hdbk-23 is a design guide for aircraft sandwich construction. It does not give mechanical properties but rather design formulas which can be used with the mechanical properties in MIL-Hdbk-5 and 17.
 - (d) The Aerospace Structural Metals Handbook is particularly useful in alloy selection. Typical mechanical properties and physical properties are given for approximately 200 alloys of interest to the aerospace industry. Quarterly supplements provide both revised and new chapters.

Special attention is paid to those factors associated with the history and service conditions which might limit the load-carrying capacity of an alloy. Thus, emphasis is placed on fracture properties, stress corrosion, hydrogen embrittlement, effects of impurities, etc. This handbook is prepared under an Air Force contract and has been under pressure from DOD to become self-supporting. As might be expected, it has been very difficult to approach this goal because of the limited nature of the market.

- (e) The Metals Handbook is a publication of the American Society of Metals. It has very broad coverage of many alloys and fabrication processes of general commercial interest, but lacks a detailed treatment of aerospace alloys.

(2) Information Centers (DOD materials oriented):

- (a) Air Force Machinability Center
Metcut Research Associates, Inc.
Cincinnati, Ohio 45209
- (b) Concrete Technology Information Analysis Center
Army Engineer Waterways Experiment Station
Vicksburg, Miss. 39180
- (c) DASA Information and Analysis Center (Nuclear Explosion Effects)
General Electric—TEMPO
Santa Barbara, Calif. 93102
- (d) Defense Ceramic Information Center
Battelle Memorial Institute
Columbus, Ohio 43201
- (e) Defense Metals Information Center
Battelle Memorial Institute
Columbus, Ohio 43201
- (f) Mechanical Properties Data Center
Belfour Stulen, Inc.
Traverse City, Mich. 49684
- (g) Nondestructive Testing Information Analysis Center
Army Materials & Mechanics Research Center (Code AMXMR-TX)
Watertown, Mass. 02172
- (h) Plastics Technical Evaluation Center
Picatinny Arsenal, Bldg. 3401
Dover, New Jersey 07801

- (i) Shock and Vibration Information Center
Naval Research Laboratory (Code 6020)
Washington, D.C. 20390
- (j) Thermophysical Properties Research Center
Purdue University, Research Park
West Lafayette, Ind. 47906

These Centers in some cases use computer facilities for the storage and classification of data taken from published sources. Some publish periodic reviews; noteworthy among these is the Defense Metals Information Center which publishes monthly reviews in many different areas of metals technology. All the Information Centers are designed for rapid response to requests for information. These Centers receive their support from the DOD Office of Deputy Director of Defense for Research and Engineering and have been under continuous pressure to become self-supporting through sale of their services. Attempts to approach this method of operation have not met with notable success because of the inherently limited nature of the market. At present these attempts are futile because of the depressed conditions of the aerospace industry.

- (3) Special handbooks—Some government organizations or their large program offices publish special handbooks that are directed to a specific application. They contain data taken from the technical literature as well as data generated for their own use. An advantage of these documents is that all engineers associated with a particular program use the same data. They have the disadvantage of specialization and frequently of relatively short life. There are many such documents. Typical examples are:
 - (a) Aircraft Designers Handbook for Titanium and Titanium Alloys published by the FAA Supersonic Transport Office
 - (b) NERVA Program, Ferrous Metals, and Metallic Materials Handbook
 - (c) JPL - Spacecraft Materials Guidebook
 - (d) MSC-02681 Nonmetallic Materials Design Guidelines and Test Data Handbook
 - (e) Advanced Composite Handbook published by the Air Force
 - (f) Cryogenic Materials Handbook published by the National Bureau of Standards
- (4) Open technical literature—The open literature in the materials field is voluminous and not well organized for use by designers. It is largely a means for communication between those engaged in research.
- (5) Company brochures—The large materials producers publish elaborate compilations of data and advertising material relating to their own alloys. These are generally useful documents although in many cases the data are poorly

defined as to form and heat treatment, and frequently only the "best" information is presented. These sources of information seldom give a thorough presentation of the problems encountered with application of a particular alloy.

- (6) Company files—Most aerospace companies maintain files of data pertinent to their programs, and much of this never gets into the widely available sources such as the Data Centers and handbooks. These files are generally proprietary, but in many cases specific requests for information will be honored. The basic problem with this source of data is that there is no way of knowing where the desired information may be located.

Accessibility of Information

Data Centers and handbooks offer an expeditious way to make the vast amount of pertinent data available to designers. However, the Air Force Data Centers and the Aerospace Structural Metals Handbook have always had a tenuous existence and a variable funding history which has not helped their efficiency. As mentioned previously, DOD expects these activities to become self-supporting, and has gradually reduced their support until at present it is about two-thirds of that in 1969. The current plans of the Office of Defense Research and Engineering are to require that the Information Centers obtain at least 50 percent of their support in fiscal year 1972 from selling their services or lose all DOD support in the future. As mentioned previously, the market for their services is inherently limited and now it is even more so. This DOD goal of 50 percent self-support during 1972 seems unrealistic, and insistence on it may spell the end of many of the Information Centers.

It seems evident that what is needed is a strengthening of these services rather than their termination. However, this should not be done by increasing their number. Further proliferation of sources would diminish rather than increase the accessibility of information. Consequently, the Panel recommends that NASA seek ways to cooperate with the Air Force and ODDRE to maintain support for selected activities including the three MIL-Handbooks, the Aerospace Structural Metals Handbook, and the Defense Metals Information Center. Improvements are desirable in two areas: (1) an increased capability to obtain data from unpublished sources such as company files, and (2) an increased coverage in terms of new alloys and more frequent updating of information on established materials. In respect to this last point, it is very important that, once a widely used handbook has been established, support should be continued.

The Aerospace Structural Metals Handbook suffers from a data accessibility problem that is probably common to other NASA and Air Force supported handbooks and data centers. This handbook is dependent for much of its information on reports issued by NASA and the Air Force either through their in-house or contract activities. At present there is no system which ensures that the Mechanical Properties Data Center, which compiles the handbook, will automatically receive pertinent reports from these activities. It would be highly advantageous if the originating Division within the Air Force and NASA would identify their research projects which generate mechanical and

physical property data pertinent to the handbook and make arrangements to place the Mechanical Properties Data Center on an automatic distribution list for reports issuing from these projects.

A problem closely related to the accessibility of information is encountered by those who attempt to use the NASA or DOD computerized facilities to search for metals property data. To be effective, such searches require access to the titles of reports that contain information on particular alloy types. Unfortunately there is no coding system in use which would permit a search using commonly accepted alloy designations. In other words, there is no way for an engineer to request titles of reports which would contain physical or mechanical property data on common alloy types such as 4340 or maraging steel. The introduction of the necessary coding systems should be a relatively easy job, and if possible they should be compatible with the coding system used in the Aerospace Structural Metals Handbook. In this way information could be more readily located by those who prepare handbook chapters.

Discipline In The Use of Information

Information that is not readily available for use by the designer at the appropriate time is of little practical value regardless of the care with which it has been catalogued. Furthermore, the designer cannot be expected to be an expert in materials behavior or in special aspects of structural analysis such as crack mechanics. Nevertheless, management cannot make a sound judgement concerning the risks of structural failure without recommendations from specialists in these fields. Their input should be injected into the program in the planning stages because it generally will have a strong bearing on the expected vehicle weight and performance. If this is deferred until well along in the project development, recommendations designed to reduce failure risks are more likely to be compromised to preserve the established weight and performance requirements.

It is obviously impossible to ensure by contractual obligation that all the special information necessary to make a sound judgement concerning failure risks as balanced against performance requirements will be available at the right time and in the right place. However, a number of steps can be taken to encourage the timely use of existing information by the program offices within NASA and by NASA's contractors. The following outlines several such steps:

- (1) Introduction of materials and structural analysis specialists into the project at the planning stage well before weight and performance requirements have become fixed. In some cases this might be done by forming Review Panels composed of specialists from NASA Centers and from appropriate outside organizations.
- (2) Development of a "Materials Selection Guide" identifying material conditions that are particularly sensitive to strength limiting factors such as stress corrosion, small flaws, fabrication processes, etc. This document should be included in contracts, and the contractor should be required to justify the use of a sensitive material condition by showing how the sensitivity will be overcome or will not increase the risk of failure.
- (3) Circulation of materials selection guides, lists of persons within NASA and other Government agencies that are specialists in selected technical areas,

and reports that specify sources of information on materials properties and new designs concepts.

- (4) Development of standard reporting methods for failure analysis and arrangement for distribution of this information to all pertinent parties. At present there is no standardized method of reporting failures nor is there an effective method for distribution of failure analyses. The result is that trends with regard to specific materials or structural types are very difficult to determine. Our present ALERT system has been successful in reporting failures in hydraulic, electric, and electronic components but has not been effectively used for structural materials. The IDEP (Interagency Data Exchange Program) has not been effective for structural materials failures either. Perhaps one of these systems could be extended to provide the necessary structures coverage. Consideration should also be given to the preparation of digests of failure experience. Such digests would provide wide dissemination of information and provide an easy opportunity to discern trends.

Conclusions and Recommendations

It is the conclusion of the Panel on Documentation and Communication of Information that the risk of failure of aerospace structures could be significantly reduced and the costs of their development decreased if the documentation and means of communication for materials information could be improved. At the present time NASA is weak in this area and has no clearly defined group whose responsibility it is to assist the program offices in locating information on failure experience, materials property data, and special structural analysis concepts. As stated previously, most of NASA's past failures were associated with conventional, well established alloys for which much pertinent data had been accumulated. It appears that in most cases where difficulties arose an important factor was the lack of information by the proper person at the proper time. The need for effective dissemination of technical information will become even more critical as NASA is forced to use new types of materials such as dispersion strengthened alloys, ceramics, and composites. Data on these new materials are relatively scarce, and almost none are in the standard handbooks. The need to transmit these data speedily from the point of origin to the user provides a further incentive to strengthen the appropriate data sources and provide ready access to them.

The Panel recommends that NASA take the following actions, designed to strengthen its position in the field of documentation and dissemination of technical information, to ensure more effective use of such information by the NASA program offices and their contractors:

1. NASA should increase its support (with other Government agencies) of selected activities that accumulate and analyze physical and mechanical property data on metals, composites, and plastics of particular interest to the aerospace industry. Examples of such activities that should be supported include the following Air Force sponsored documents:

- a. The Aerospace Structural Metals Handbook
 - b. MIL-Handbooks 5, 17, and 23
 - c. The Defense Metals Information Center
2. NASA should contractually require that:
 - a. A failure mode analysis be conducted for all major structural components and that the contractor demonstrate the existence of a fracture control program and the means for its implementation
 - b. The data and the sources of data used for design be reported
 - c. Material specialists be used in the drawing approval chain for all potentially critical structural components
3. NASA should take the steps outlined in the previous section of this appendix to encourage the timely use of technical information by NASA program offices and their contractors.
4. NASA should continue and expand its structural design criteria program to ensure that criteria are prepared on a time schedule consistent with project needs. NASA should encourage the use of these criteria by project offices.
5. NASA should cooperate with the appropriate technical society and government agencies to establish standardized materials specifications that meet its needs.
6. NASA should consider preparing a series of courses (possibly on film) of selected subjects that are closely related to critical problem areas. These should be distributed to both NASA Centers and contractors. It would be desirable to require contractually the key people in design groups to take such courses.
7. It is recommended that an office be designated in OART (possibly in the Materials and Structures Division) to define more fully and implement these specific recommendations. This office would, of course, draw on the expertise at NASA Centers and program offices in carrying out its work.

**APPENDIX D: Authorization for the Committee and
Committee Membership**

APPENDIX D: AUTHORIZATION FOR THE COMMITTEE AND MEMBERSHIP

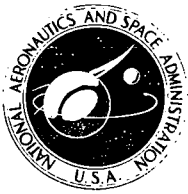
The Committee was established on June 22, 1970 by the Acting Administrator for Advanced Research and Technology (attachment A) in response to a request from the Deputy Administrator in a memorandum dated April 28, 1970 (attachment B).

The membership of the Committee is as follows:

Chairman, William R. Lucas, NASA Marshall Space Flight Center
Vice-Chairman, G. Mervin Ault, NASA Lewis Research Center
Secretary, Richard H. Raring, NASA Headquarters
William F. Brown, Jr., NASA Lewis Research Center
Patrick T. Chiarito, NASA Lewis Research Center
Thomas V. Cooney, NASA Headquarters
George C. Deutsch, NASA Headquarters
Herbert F. Hardrath, NASA Langley Research Center
Richard R. Heldenfels, NASA Langley Research Center
Robert E. Johnson, NASA Manned Spacecraft Center
Merland L. Moseson, NASA Goddard Space Flight Center
Robert A. Wasel, NASA Headquarters
Howard M. Weiss, NASA Headquarters
R. F. Hoener, WPAFB, Flight Dynamic Lab.
J. J. Mattice, WPAFB, Materials Lab.

The composition of the Committee reflects special knowledge in the following areas:

- (1) Structural materials used in NASA aerospace vehicles and ground support equipment
- (2) Mechanical properties of materials including fracture resistance
- (3) Failure investigations and analysis
- (4) Activities of the NASA Offices of R&QA and Design Criteria
- (5) Nearly all of NASA's space flight programs



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF:

RV

June 22, 1970

TO: Distribution List

FROM: R/Acting Associate Administrator for Advanced
Research and Technology

SUBJECT: NASA Ad Hoc Committee on Failure of High-Strength
Structural Materials

I am convening, and appointing the addressees to, the subject committee to examine NASA's past and possible future troubles with high-strength structural materials. The committee's charge and composition will be as stated in the enclosed notes of the June 8, 1970 meeting at NASA Headquarters. The circumstances that led to that meeting, and other pertinent background material, appear in the attachments to the notes to that meeting.

The first meeting of the committee will be held at NASA Headquarters at 9:30 a.m. on Wednesday, July 1, 1970, in Room 521J, FOB-10B. The agenda for this meeting is attached.

The appointments of the representatives from the NASA Centers have been requested through their Center Directors. I am advising them of this action by a copy of this letter.

Oran W. Nicks

Attachments

Distribution:

RA/William S. Aiken, Jr.
RPM/Robert A. Wasel
RR-1/George C. Deutsch
RRM/Richard H. Raring
RVA/Thomas V. Cooney
RY/H. Kurt Strass
KR/Howard M. Weiss

Information:

GSFC/Merland L. Moseson
GSFC/Robert R. Ziemer
LaRC/Herbert F. Hardrath
LaRC/Richard R. Heldenfels
LeRC/G. Mervin Ault
LeRC/William F. Brown, Jr.
LeRC/Irving I. Pinkel
MSC/Robert E. Johnson
MSFC/William R. Lucas

AGENDA

NASA AD-HOC COMMITTEE ON FAILURE OF HIGH STRENGTH STRUCTURAL MATERIALS

Washington, D. C., FOB 10B, Room 521-J

July 1, 1970 - 9:30 AM

- I How Committee Came Into Being
- II Objectives of Committee
 - A. Documentation of Failures
 - B. Define Needed New Research
 - C. Examine Needs for Publication and Distribution of Engineering Data
- III Rationale of Composition - Members Selected Chiefly for Items:
 - A. Documentation Role -
 Lucas, Hardrath, Johnson, Moseson, Weiss, Ziemer
 - B. New Research Needs -
 Ault, Aiken, Brown, Deutsch, Heldenfels, Pinkel, Wasel
 - C. Data Publication -
 Ault, Brown, Cooney, Deutsch
- IV Modus Operandi
- V Expected Life of Committee and Number of Meetings Needed
- VI Assignments
- VII Next Meeting
- VIII Adjourn



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO
ATTN OF:

Office of the Administrator

April 28, 1970

MEMORANDUM

TO: R/Acting Associate Administrator for Advanced Research
and Technology

FROM: AD/Deputy Administrator

SUBJECT: Materials Problems

When you first moved to OART, I discussed with you my concern about materials in the context of problems that were now appearing on the F-111, C-5A, etc.

As I recall, I related to you some of the materials problems that we had encountered in Apollo and asked what was being done by NASA to collect and publish all that is now known about the application of new high-strength materials. There probably wasn't a single instance where we used a new material in a high-strength application in Apollo where we didn't subsequently run into some sort of a major problem. Somehow we learned to live with these problems or to do something about them, but we never really took time to publish what we had learned.

Bob Seamans' letter of April 17, 1970, (with action assigned to OART) again reminded me of the subject. I think we should certainly support the Air Force and work with them in this matter, as Bob Seamans suggests. But even more important, I think that NASA should start a strong in-house effort in this area. If you have not had a chance to do anything about this since our original discussion, I would suggest that you convene an ad hoc task group, including Bill Lucas from Marshall, Joe Kotanchik from MSC, Ault Brown from Lewis, and others from other Centers. The task group's charter should be to collect information that has become available during the past two or three years and see to it that it is published as quickly as possible. Further, the task group should look at the area as a whole, with a view toward determining what additional research NASA should perform. (In light of the Apollo 13 accident, I would imagine that Lucas and Kotanchik will not be available during the next several weeks.)

I would also like to discuss with you the membership that we would propose for the steering or executive committee mentioned in Bob Seamans' letter before we make any final decisions in this matter.

Please call me when you have had a chance to think this over.

George M. Low